BIOMECHANICAL AND CLINICAL STUDIES ON ACRYLIC AND EPOXY-PIN EXTERNAL SKELETAL FIXATION SYSTEMS IN DOGS

Thesis

Submitted in partial fulfilment of the
requirement for the degree
of
Doctor of Philosophy
in
VETERINARY SURGERY AND RADIOLOGY

By
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Roll No. 1218

To
DEEDED UNIVERSITY
INDIAN VETERINARY RESEARCH INSTITUTE
Izatnagar – 243 122 (U.P.)
2011

भारतीय पशु चिकित्सा अनुसंधान संस्थान
(सम विश्वविद्यालय)

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Certificate

Certified that the research work embodied in this thesis entitled **"Biomechanical and clinical studies on acrylic and epoxy-pin external skeletal fixation systems in dogs"** submitted by **Dr. Surbhi, Roll No. 1218,** for the award of **Doctor of Philosophy Degree** in **Veterinary Surgery and Radiology** at **Indian Veterinary Research Institute, Izatnagar,** is the original work carried out by the candidate herself under my supervision and guidance.

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It is further certified that the candidate has completed all the prescribed requirements governing the award of Ph.D. Degree of the Deemed University, Indian Veterinary Research Institute, Izatnagar.

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Acknowledgements

It is a pleasure to thank those who made this thesis possible. In the first place I would like to record my sincerest gratitude to my mentor cum major advisor ***Dr. H. P. Aithal****, Senior Scientist, Division of Surgery and Radiology, IVRI, Izatnagar for rendering dexterous guidance, valuable suggestions and perceptive enthusiasm during the course of my study. I am grateful to him for constant inspiration. He has taken pain to go through the research work and make necessary corrections as and when needed.*

A special note of thanks towards my Co-advisor ***Dr. P. Kinjavdekar****, Principal Scientist, he has cared for my well being like a guardian with love and affection. Apart from the subject of my research, I learnt a lot from him, which I am sure, will be useful in different stages of my life*

A special note of thanks towards my Co-advisor ***Dr. Amarpal****, Senior Scientist, for his active interest, intense involvement and painstaking guidance right from the inception till the completion of this study.*

I would like to express my gratitude to the other members of my thesis advisory committee ***Dr. S Dey****, Head & Principal Scientist, Division of Medicine,* ***Dr. D. B. Mondal****, Principal Scientist, Division of Medicine and* ***Dr. A.G. Telang****, Principal Scientist, Division of Pharmacology and Toxicology for much help with the research design and methodology.*

The kind of moral support, well wishes and constant encouragement which was given to me from ***Dr. A.M. Pawde****, Principal Scientist, for his review and many helpful comments at different stages of my study is highly acknowledged.*

I am also thankful to ***Dr. M.M.S. Zama****, Professor and Head, Division of Veterinary Surgery and Radiology, IVRI for his constructive suggestions and providing all the necessary facilities for completion of the work.* ***Dr. (Major) K. Pratap*** *and* ***Dr. O. P. Gupta*** *former Heads, Division of Veterinary Surgery and Radiology, IVRI, Izatnagar will be remembered always for their active interest and valuable suggestions.*

A Special thanks to ***Dr. M. Hoque****, Principal Scientist, for his caring and supportive attitude. I offer my sincere thanks to Scientists of my division* ***Dr. A. K. Sharma****,* ***Dr. Naveen Kumar****,* ***Dr. S. K. Maiti****,* ***Dr. Rekha Pathak****,* ***Dr. A. Gopinathan*** *and* ***Dr. Abhishek Saxena****, for their advice and suggestions. I like to express my sincere thanks to the Technical Officer (Radiology) Mr. H. C. Setia for his support.*

I am highly thankful to the ***Director*** *and* ***Joint Director (Academic)****, Deemed University, IVRI, for providing the necessary facilities to carry out my research work.*

I express my thanks to the authorities of Krishna Institute of Engineering and Technology-Ghaziabad, where biomechanical testing of the fixator constructs was done. My deep sense of gratitude is for Dr. K.P. Tyagi, Professor & Head and Mr. Tuhin Srivastava, Lecturer, Department of Mechanical Engineering for extending their support and guidance. I would like to thank and appreciate the helpful students of KIET, Prabhakar Pathak, Himanshu Khullar, Ambesh Sharma and Jitendra Singh Gaur for their support in the course of testing the samples.

I am indebted to my many of my colleagues to support me; Warson and Madhu need a special mention here for their continuous help and moral support during my research. I would also like to thank Jasmeet Singh for helping me in purchasing the raw materials for models. I am grateful to Gangwar sir, Shahnawaz, Irawati & Mritunjay for helping me in my research work.

G.D. Sir, Rahul Sir, Tiwari Sir, Dr. Moin. Ansari, Dr. Ansar Ahmed, Ranjeeth and Dilip Sir will always be remembered for their unfailing support and help. I would like to express my thanks to the cheerful company provided by my loving juniors Dr. Raja Aijaz, Mudassir, Shiv kumar, Karthik, Siddharth, Rohit, Girraj, Mathew, Ninu, Remya, Vineet, Arundeep, Shivnarayan and John.

Renuka madam (Mrs. Kinjavdekar) will always be remembered for her love and affection. Thanks to Hridya mam, Rajat Sir and Mr. Aziz Khan (Faculty SRMS-Engineering College) for helping me in standardization of mechanical testing procedures, in the initial phase of my study. I would also like to thank Mr. S. Begh, who had helped me in making models for the study.

I am highly thankful to Mr. Dhamendra for meticulous typesetting and designing of the thesis.

I thank the staff of surgery Division-Pandey ji, Pradeep, Chauhan, Tara Singh, Nissar and Dorilal for their assistance in this work.

My time at IVRI was made enjoyable in large part due to friends and groups that became a part of my life. The hidden affections, love, care, worthful suggestions and help I got from my friends Simran didi, Joken didi, Nitika didi and Tumnyak cannot be expressed in words.

I can never forget the colourful company of my friends at IVRI- Drs. Renuka, Bizunish, Vandana didi, Vinita didi, Subhashree, Ladol, Kani mam, Indira didi and Reena. I cannot acknowledge the pleasure of association with my friends Kawardeep, Monika, Sukhleen, Deepanjali, Pankaj, Latima, Kusum and Nasreen for their love, care and support during the entire period of my study. I would also thank my friends

Shashank, Aman, Bhavesh, Umesh, Rajeev, Dilip, Mohd Iqbal, Mohd Ibrahim, Shaheen, Gaurav Singh, Ajitpal and Durgesh for their constant care and support.

I express my gratitude to Dr. M. S. Bhadwal, Dr. Ajay Gupta, Dr. Anish Yadav and Dr. Harjeet Singh for their moral support, care and encouragement throughout this study period.

The motivation and constant encouragement given by my family members has made many difficult tasks easier for me. Special thanks for Mummy and Papa for showering their love and blessings on me. I am grateful to Pradeep Bhaiya & Laxmi Bhabhi; Sandeep bhaiya & Kavita Bhabhi; Poonam didi & Jija ji and Teena didi & Jija ji who have made available their support in a number of ways right from inception to completion of my work. The love and support shared by my family has strengthened my mind. The cheerful and colourful company provided by Shivank, Devanshi, Dev, Tejas, Vishesh and Vanika has made my time pleasant when working.

The blessings of Pallavi didi & Jija ji; Aarushi & Chetan; Sham Gupta; Varchas gupta amd my brother Aditya and will be remembered without which I would never have been what I am today. I owe immensely to my Papa whose loving memories are always besides me giving me inspiration, strength and moral support. I also admit myself being incapable to pay regards in words to the affection, blessings, encouragement and dedication of Mummy.

Words fail me to express thanks to my loving, supportive, encouraging, and patient husband Dr. Kuldeep Tyagi whose faithful support during the Ph.D. is so appreciated. This work would have been impossible without his support. Thanks for being with me.

Above all, I remember my Almighty who gave me strength, courage and perseverance to achieve this goal.

Finally, I would like to thank everybody who was directly or indirectly involved in the successful completion of thesis, as well as expressing my apology that I could not mention them personally.

Thank you.

Date:

Place : Izatnagar **(Surbhi)**

Abbreviations

% : Per cent
@ : At the rate
< : Less than
> : More than
AC : Acrylic circular
ALP : Alkaline phosphatase
AM : Acrylic multiplanar
AU : Acrylic uniplanar
Ca : Calcium
cm : Centimeter
EC : Epoxy circular
EM : Epoxy multiplanar
et al. : and others
EU : Epoxy uniplanar
Fig. : Figure
g/dl : Gram per deciliter
Hb : Haemoglobin
i.m. : Intramuscular
i.v. : Intravenous
kg : Kilogram
KN-mm : Kilonewton millimeter
Lt. : Left
mg/dl : Milligram per deciliter
min. : Minute
mm : Millimeter
mm/sec. : Milimeter per second
mmol/L : Millimol per liter
N/mm : Newton per millimeter
N/mm^2 : Newton per millimeter square
Nm : Newton meter
No. : Number
°C : Degree calcius
P : Phosphorus
$P<0.05$: Significant at 5%
$P>0.05$: Significant at 1%

PCV : Packed cell volume
PVC : Polyvinyl chloride
R/U : Radius/Ulna
rpm : Revolutions per minute
Rt. : Right
RTA : Road traffic accident
SE : Standard error
T/F : Tibia/Fibula
TTM : Torsion testing machine
UDL : Uniformly distributed load
UHDPE : Ultra high density polyethylene
Units/L : Units per liter
UTM : Universal testing machine
θ : Theta
τ : Torque

Contents

INTRODUCTION

External skeletal fixation (ESF) is a method of immobilization of fractured bone using percutaneous pins that are connected outside the body to form a rigid frame or scaffold (Van-EE and Geasling, 1992). External skeletal fixators are used for the treatment of fractures which are difficult to reconstruct anatomically, for arthrodesis, for stabilizing corrective osteotomies and for bone lengthening procedures (Harari, 1992; Aron *et al.,* 1995; Lewis *et al.,* 2001).

External skeletal fixators are widely used in small animal practice and have several advantages over other modalities, like they help in preserving neurovascular structures and soft tissue, cause minimal damage to injured site, maintain bone length and allow biological osteosynthesis (Egger, 1983; Lewis *et al.,* 2001). The wound management in case of open fractures with procedures like debridement, lavage, drainage along with skin grafting and bone grafting can be performed well with external skeletal fixation (Ueng *et al*., 1999; White, 1999).

External skeletal fixators of various designs and types have been used for fracture treatment based on fracture location, bone involved and fracture type. In general, external skeletal fixators can be of linear, circular or hybrid designs. The first and the most commonly used external skeletal fixator system in veterinary orthopaedics is Kirschner-Ehmer splint (Pettit, 1992). The components of external skeletal fixators are pins, connecting bars and pin gripping clamps (Boothe and Tangner, 1983). It is either in uniplanar or bi/multi-planar configurations, and unilateral or bilateral configurations. The strength of the fixation frame increases with the increase in the complexity of the fixation frame (Johnson and DeCamp, 1999). Circular (Ilizarov model) and hybrid designs have been more versatile and found to provide stable fixation of unstable fractures (Paley, 1991; Clary and Roe, 1995; Lewis *et al.*, 1998; Marcellin-Little, 1999).

Generally the components of the external skeletal fixators were made of a metal, most commonly stainless steel. Other materials used include aluminum, titanium and carbon fibers, which are of relatively light in weight. However, carbon components are expensive. The major disadvantage associated with ESF made of metal is their high cost, heavy weight and their fixed frames which offer less versatility in shape and direction. The size and shape of the side bars/rings remain the same. Also, the diameter of the transosseous pins is dictated by the size and location of the clamps or rings.

Several modifications were made in the external skeletal fixators even for better use in clinical situations. One of such modifications is replacement of the metallic connecting bars and clamps with the non-metallic substances. Different materials used to design ESF components for use in veterinary patients, including polymethylmethylacrylate (PMMA), epoxy putty and automotive body filter (Tomlinson and Constantinescu, 1991; Roe and Keo, 1997; McCartney, 1998; Worth, 2007). Use of these substances provides several advantages to the external skeletal fixators like light weight, less expensive and the pin direction need not be influenced by the direction and location of the connecting bar/ring. Also the pin diameter is not limited by the clamp size (Okrasinski *et al*., 1991).

Acrylic resin was initially used in the construction of components of the external skeletal fixators for human and veterinary patients (Green, 1989; Worth, 2007). They were used in the repair of mandibular fractures of small animals (Chambers, 1981; Stampley and Lawrence, 1993). Among acrylics, dental acrylic or horse hoof repair products were often used (McCartney, 1998). Except for medical grade acrylics (which contain barium sulphate) most acrylics are radiolucent, which facilitates postoperative assessment of fracture site (Lewis *et al.*, 2001).

Epoxy adhesive and cast materials have also been used to construct free-form external fixators in birds (MacCoy, 1981; Bennet and Kuzma, 1992; Roe and Keo, 1997). More recently, epoxy-pin fixator constructs have been used successfully for treatment of compound fractures in dogs, small ruminants and calves (Kumar, 2007, Aithal *et al.*, 2009; Kumar *et al*., 2011).

Biomechanics is the study of the structure and function of biological systems by means of the methods of mechanics (Hatze, 1974). In clinical practice the fractures encountered are more commonly a product of a combination of the forces/loads. Long bones mostly fracture under the influence of compression, bending and torsional loads.

For clinical acceptance, an ESF must be sufficiently rigid, well tolerated, easily applied, and inexpensive (Singh *et al*., 2007). Fixator rigidity depends on the design and the material used to construct the fixator, and hence it varies among different fixator constructs (Johnson and DeCamp, 1999; Singh *et al*., 2007). Biomechanical studies have revealed that the acrylic fixator is stronger in axial, craniocaudal and torsional loads and as strong in mediolateral bending loads compared with stainless steel equivalent (Willer *et al*., 1991). Roe and Keo, (1997) based on their biochemical study suggested that epoxy putty can be a suitable material for connecting pins in free-form external skeletal fixators. Nevertheless, very less work has been done on the use of acrylic and epoxy in free form external skeletal fixators for treatment of long bone fractures in dogs and on their biomechanical aspects. The present study was therefore, planned with the following objectives:

1. To design and develop suitable techniques of external skeletal fixation using acrylic and epoxy as external fixator components for treatment of long bone fracture in dogs.
2. To study the comparative *in vitro* biomechanical properties of different designs of acrylic and epoxy-pin external skeletal fixation systems.
3. To evaluate a suitable design of acrylic and epoxy-pin external skeletal fixators in the treatment of long bone fractures in clinical cases.

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REVIEW OF LITERATURE

External skeletal fixation (ESF) is a method of treating bone and joint injuries as well as correcting skeletal deformities by attaching bones to an external device that stabilizes the injured limb (Marcellin-Little, 1999). It allows manipulation of the limb segments to achieve restoration of length and alignment. A synonym for external skeletal fixation is “external osteosynthesis”. In contrast, internal osteosynthesis employs devices implanted under the skin and muscle. External braces, cast splints and orthotic devices are not considered external fixators.

External skeletal fixation is most commonly used for fracture management. ESF may be applied using either closed or open fracture reduction and are often used for highly comminuted fractures that cannot be reconstructed anatomically (Marcellin-Little, 1999). They also facilitate management of associated soft tissue injuries, making ESF ideally suited for the treatment of open fractures. ESF is also commonly used in combination with other forms of internal fixation (usually intramedullary Steinmann pins and/or cerclage wires) to provide adjunctive fracture stabilization. Other indications for the use of these systems include the treatment of non-union and infected fractures, the correction of limb deformities, the stabilization of arthrodeses, and the transarticular immobilization of joints following ligament or tendon repair (Lewis *et al.,* 2001). ESF along with osteotomy of radius and ulna has been used to correct angular limb deformities (Marcellin Little *et al*., 1998; Singh *et al*., 2008).The use of external skeletal fixators was once associated with complications and postoperative morbidity. But clinical and experimental studies have led to technological advances and modifications in application techniques, which have greatly reduced the complications associated (Marcellin-Little, 2002).

When placing an external fixator, preoperative planning is essential. Damage to existing anatomic structures, including muscles, tendons, nerves and vessels, must be avoided or minimized. Anatomic safe zones for pin insertion are suggested to avoid such damage. Usually, the safe zone is in the area of bone that is most superficial, with the fewest number of neurovascular structures in the vicinity (David and Nirmal, 2007).

The external skeletal fixators can be of linear, circular or hybrid (combination of linear and circular) type. If the connecting rods or rings are replaced by some non-metallic polymeric material, then the fixator is called as free-form of external skeletal fixator.

Linear external skeletal fixators

The basic linear external fixator frame is composed of connecting rods and a series of connecting clamps (Lewis *et al.,* 2001). Single connecting clamps are used to fasten fixation pins to connecting rods. Double connecting clamps are used to fasten connecting rods to one another. External fixators are modular systems and thus can be assembled in numerous construct configurations (Lewis *et al.,* 2001). Main factors that affect the stiffness and various loads resisting capacity of the linear ESF system depends on the pin factors, connecting bar material and frame configuration(Lewis *et al.,* 2001).

Pin factors

Pins and wires connect sidebars and clamps to bone and are a critical link in the stability of external fixation. The weakest link in the ESF system is the bone-fixation pin interface (Briggs and Chao, 1982, Aron *et al.,* 1986). Pin factors include pin type, size, length, number, location and pin insertion technique.

Pin type/design is an important parameter affecting bone-fixation pin stability (Anderson *et al.,* 1997). Non-threaded or partially threaded pins can be used as fixation pins. Non-threaded fixation pins have significantly less resistance to axial extraction in cortical bone when compared with partially threaded fixation pins (Egger *et al.,* 1986; Bennett *et al.,* 1987) and thus are prone to loosening during the convalescent period, resulting in pin tract drainage and patient discomfort (Aron *et al.,* 1986). Clinically, the increased stability afforded by the use of partially threaded pins decreases the risk of complications associated with premature loosening of fixation pins (Aron *et al.,* 1986; Anderson *et al.,* 1993). Partially threaded pins can have the thread positioned at the end of the pin (used for half-pin splintage) or centrally on the pin (used for full-pin splintage) (Anderson *et al.,* 1997). Ellis or SCAT pins, which have cutting threads only along a short length (approximately 1 cm) of the tip of the pin facilitates placement of the thread smooth shaft interface within the medullary cavity, thereby protecting this interface from bending forces during weight bearing (Bennett *et al.,* 1987).

Initially, most partially threaded fixation pins were negative profile (Anderson *et al.,* 1997). Positive profile fixation pins are also purported to have superior axial extraction resistance characteristics to negative profile pins (Palmer *et al.,* 1991, Anderson *et al.,* 1993). Positive profile fixation pins have been designed with both cortical and cancellous thread profiles. The cancellous thread profile was developed to be placed in regions of the bone that are composed of predominantly cancellous bone, such as the proximal tibia, proximal humerus and distal femur (Anderson *et al.,* 1997). In addition, positive profile pins can be manufactured to function effectively as both centrally threaded full-pin splintage pins and end threaded half-pin splintage pins, whereas negative profile pins can only effectively function as end threaded half-pin splintage pins.

Pin size/diameter increases the fixator stiffness directly. Pin's stiffness is proportional to its core diameter to the power of 4 (Nunamaker *et al.,* 1986; Bennett *et al.,* 1987; Muir *et al.,* 1995). The pin diameter should not exceed 25 % (20-30%) of the bone diameter (Edgerton *et al.,* 1990). Shorter pins are stiffer than long pins because pin stiffness is inversely proportional to pin length to the third power (Bouvy *et al.,* 1993).

Number of fixation pins in the proximal and distal major bone fragments influences the fixators' stiffness and affects the distribution of the physiologic loads among pins. The greater the number of fixation pins per fragment, the more effective is the device in stabilizing the fracture and maintain pin-bone interface integrity (Smith, 1985; Palmer *et al*., 1991; Bouvy *et al*., 1993). This is true up to four pins per major proximal and distal fragments; beyond this number the increase in mechanical advantage is negligible (Palmer *et al.,* 1991; Bouvy *et al.,* 1993).

Locating pins both close to the fracture and at the end of the bone increases the stiffness and decreases the motion at the fracture site. This principle is far-near-near-far principle and is universal for all type of ESF systems (Bouvy *et al.,* 1993; Marcellin-Little, 2002).

Pin fixation technique can vary from using a hand chuck, low speed drill or high speed drill and has a substantial effect on the integrity of the bone-fixation pin interface (Egger *et al.,* 1986; Gumbs *et al.,* 1988; Clary and Roe 1995, 1996). Fixation pins (non-threaded) placed using a hand chuck had inferior acute axial pull-out strength and were loose when compared with those pins placed using a low speed (150 rpm) power drill (Gumbs *et al.,* 1988). Egger *et al.* (1986) found that the mechanical damage was more near pins inserted using a hand chuck on histological examination. High speed (1200 rpm) power drill also had significantly lower axial extraction forces, which was ascribed to thermal necrosis of bone surrounding these pins placed at high speed (Egger *et al.,* 1986). So, it is advantageous to use low speed power drilling of the pins.

Pre-drilling a pilot hole to facilitate the placement of fixation pins has been suggested as another means of further improving the bone-fixation pin interface (Clary and Roe, 1995, 1996; Anderson *et al.,* 1996). A pilot hole of substantially smaller diameter than the core of the fixation pin reduces axial micro motion as a result of circumferential compressive interaction between the fixation pin and the bone, referred to as ‘radial preload’ (Biliouris *et al.,* 1989). Conversely, a pilot hole exceeding the core diameter of the fixation pin reduces mechanical bone trauma during insertion (Clary and Roe, 1996).

Clary and Roe (1996), in a study designed to define the optimal pilot hole diameter for a positive profile partially threaded fixation pin, found that the excessively small pilot holes were causing micro-structural damage that occurs during pin insertion in such cases, whereas, pilot holes that exceeded the core diameter of the fixation pin resulted in decreased initial pull-out strength. Thus, pre-drilling of a pilot hole that approximates, but does not exceed, the core diameter of the fixation pin was recommended. This represents a compromise between maximizing the initial pull-out strength and minimizing insertional bone damage.

Connecting bar material

Conventional ESF systems are made of metals most commonly stainless steel (Kummer, 1990). The other available metals are aluminum, titanium and carbon fibers. Carbon fiber, titanium and aluminum weigh less than comparable diameter of stainless steel rods. These metals are also having more stiffness than stainless steel (Lewis *et al.,* 1998; White *et al.,* 2003; David and Nirmal, 2007). Carbon fibers are radiolucent and comparatively stiffer than other metals available (Nele *et al.,* 1994; Lewis *et al*., 1998; David and Nirmal, 2007). But it is very expensive and in addition, once used the carbon rods cannot be reused (White *et al.,* 2003).

Frame configurations

External fixators have been classified as being either type I, II or III configurations (Roe, 1992). Type I configurations utilize half-pin splintage fixation pins, which pass through both cortices of the bone but only penetrate one skin surface. The connecting frame is placed on only one side of the limb and thus these are unilateral constructs. Type II configurations utilize full-pin splintage fixation pins, which penetrate both cortices of the bone and opposing skin surfaces. Connecting frames are placed on both sides of the limb and thus these are bilateral constructs. Type III configurations utilize a combination of half-pin and full-pin splintage. Type I and II systems are placed at approximately 90^0 to each other and the frames are interconnected; these are therefore trilateral constructs.

External fixators can also be classified as either uniplanar or biplanar configurations. If all the fixation pins and the connecting frame occupy a single plane, then the fixator is uniplanar. Type II configurations are uniplanar. Most type I configurations are uniplanar (type Ia), however, if two half-pin splintage fixators are placed at 60^0 to 90^0 of axial rotation to each other and the frames are interconnected, then the resultant type Ib configuration is biplanar. Type III configurations are also biplanar (Lewis *et al.,* 2001). Types I and II are single-plane. All the other frame types are multiplanar.

Linear external skeletal fixation systems

The Kirschner-Ehmer (KE) splint was introduced in 1947 and for the past half century has been the most frequently used ESF system in dogs and cats (Pettit, 1992). Kirschner-Ehmer systems are manufactured in three sizes small, medium and large.

Use of type II and III constructs, however, is principally limited to applications distal to the elbow and stifles because of impingement by the medial connecting system on the body wall (Anderson and Aron, 1998). An alternative method is to employ the type Ia KE splint as adjunctive stabilization to an intramedullary pin. This results in a substantial improvement in the fixation biomechanics, in comparison with either fixation method alone, and often allows for early removal of the external fixator (Vasseur *et al.,* 1984; McPherron *et al.,* 1992).

Stability can be significantly improved if the intramedullary pin is left protruding through the skin surface (i.e. at the shoulder or hip) and incorporated or 'tied-in' to the external fixator frame (Aron *et al.,* 1991). This 'tie-in' construct also prevents intramedullary pin migration; however, some surgeons have complained of the development of large skin wounds over the hip when this construct was used to repair femoral fractures (Lewis *et al.,* 2001).

Several new ESF systems have been developed to address many of the deficiencies of the Kirschner- Ehmer splint; specifically, the inability to place positive profile fixation pins directly through fixation clamps, the inability to add or remove individual centrally located fixation clamps without completely removing the connecting rods, the relatively weak connecting rods, the lack of a convenient system for pre-drilling pilot holes for fixation pins, the lack of a system facilitating consistent accurate placement of multiple full-pin splintage fixation pins in the same transverse plane, and impaired visualization of osseous structures on radiographs through frame components.

IMEX Veterinary (Longview, TX, USA) introduced its SK system in 1997. In this system, the diameter of the connecting rod has been markedly increased (small rod 6-3 rnm; large rod 9.5 mm) to improve the biomechanics of the fixator frame (Bronson *et al.,* 1999; White *et al.,* 2003). SK connecting rods are manufactured from carbon fiber, titanium and aluminum, and weigh less than comparable diameter stainless steel rods. Carbon fiber and aluminum rods have the added advantage of being radiolucent. The SK fixation clamps have a two-piece clamp body, which can be readily assembled and disassembled. This also allows stable fixation irrespective of fixation pin angle and allows the use of fixation pins of varying diameter. The hole in the fixation bolt is large enough to accommodate direct placement of appropriate diameter positive profile partially threaded fixation pins.

The Securos ESF System (Securos; Fiskdale, MA, USA) was introduced in 1997. The Secur-U clamp consists of three components. The U-shaped component is the body of the clamp. The head component engages the fixation pin and secures the connecting rod within the U-shaped component. The third component of the clamp is a bolt which secures the head component within the U-shaped component. Unlike Kirschner-Ehmer clamps that deform upon tightening, the U-shaped component provides a more secure fixation to the connecting rod (Kraus *et al*., 1998b). The Securos clamp can be assembled and disassembled, and does not need to be preloaded on the connecting rod before application. The Securos system includes an aiming tool that facilitates construction of type II fixators. This aiming device has a drill sleeve attachment to facilitate drilling pilot holes for the placement of positive profile fixation pins.

Clinical results reported using the Securos system in 10 dogs with distal limb fractures found that the system simplified application, was associated with shortened surgery times and rapid times to union, and there was a low incidence (16 per cent) of fixation pin loosening (Kraus *et al.,* 1998a). Decreasing the stability of the fixator frame during bone healing has been shown to accelerate the healing process (Egger *et al.,* 1993). The Securos system allows two unique methods of altering frame stiffness without removing fixation pins. First, augmentation plates, which are made in six different lengths, have been designed to be attached to the connecting clamps of type I constructs to enhance initial frame stiffness. Secondly, if a type II fixator is applied, the bolts of the fixation clamps distal to the fracture can be replaced with slightly longer bolts. The longer bolts will engage the fixation pin, but release interference with the connecting rod.

Circular external skeletal fixators

Developed by the Russian physician, Gavriil Ilizarov, these modular systems can be assembled in numerous configurations, which can be used to stabilize fractures and arthrodeses, and to perform bone lengthening and transport, as well as to correct angular and rotational deformities (Ferretti, 1991; Welch and Lewis, 1999). Circular external skeletal fixator (CESF) systems are being used in dogs and cats (Marcellin-Little *et al.,* 1998; Lewis *et al.,* 1999a, b; Tommasini Degna *et al.,* 2000).

CESF frames consist of a series of complete and/or incomplete rings that are interconnected by threaded rods. Each ring is secured in position along the rod by placing a nut on either side of the ring (Lewis *et al.,* 1998). CESFs are uniquely designed to perform distraction osteogenesis (Welch and Lewis, 1999). The frame can be elongated or shortened to distract or compress osteotomies or fractures (Bianchi-Maiocchi, 1994). If an osteotomy is distracted at the proper rate (approximately 1 mm/day) and rhythm (fractionated into two to four equal time intervals), regenerate bone is produced within the distraction gap (Stallings *et al.,* 1998; Welch and Lewis, 1999).

Main factors that affect the stiffness and various loads resisting capacity of the CESF system depends on the ring factors, material of the construct and pin factors (pin or pin number, pin location, pin size and pin tension).

Ring diameter, which dictates pin length, has a profound influence on the mechanical properties of the CEF (Gasser *et al.,* 1990; Kummer, 1992; Bronson, 1995). As ring diameter increases, the length of the pin spanning the ring must also increase, thereby decreasing stability. Ilizarov's original recommendation to select the smallest diameter ring possible, leaving a minimum of 2 cm distance between the skin and the inner circumference of the ring to allow for soft tissue swelling and facilitate pin tract care is still applicable (Paley, 1991; Ilizarov, 1992; Kummer, 1992). Configurations that secure individual bone segments at a minimum of two levels (double-ring block) significantly increase the stability of fixation when compared with configurations that secure individual bone segments at only one level (single-ring block) (Calhoun *et al.,* 1992; Bronson, 1995).

CEF rings have been fabricated from stainless steel, aluminum, and carbon composite. Stainless steel is the most common material used to make CEF rings (Kummer, 1990). Although the aluminum and carbon composite rings must be thicker than stainless steel rings to maintain comparable rigidity, aluminum and carbon composite rings are lighter in weight and also have the advantage of being relatively radiolucent (Kummer, 1990; Nele *et al.,* 1994). Carbon composite rings, however, are substantially more expensive than aluminum or stainless steel rings (Nele *et al.,* 1994). In addition, carbon composite rings can delaminate when pins are directly clamped to the ring and thus carbon rings cannot be reused.

Unlike linear systems, CESFs classically use small diameter K-wires, rather than pins, as fixation elements (Bianchi-Maiocchi, 1994). Wires are typically tensioned to improve their stiffness characteristics (Ilizarov, 1992). No tensioning is recommended for patients weighing less than 5 kg. For 5-10 kg, 10-20 kg and more than 20 kg patients a tension of 20-30 kg, 30-60 kg and 60-90 kg is recommended, respectively (Lewis *et al.,* 1998). The tensioned wires immobilize the bone segments and adequately resist bending, shear and torsional forces, while allowing axial micromotion at the osteotomy-fracture site (Paley, 1991). Axial micromotion is considered to be important in creating a mechanical environment conducive to osteogenesis, and is purported to enhance fracture healing (Lewis *et al.,* 1998; Welch and Lewis, 1999).

Increasing the number of fixation pins increases the stability of the fixation. Orbay *et al.* (1992) found the axial and torsional rigidity of a single-ring construct was directly proportional to the number of pins used in the construct. Single-ring blocks typically use two pins that are placed on opposite surfaces of the ring. Additional pins often referred to as drop pins can be placed on either side of a ring if posts are used. Drop pins also improve resistance to bending forces (Nele *et al.,* 1994).

Pin strength and stiffness increases proportional to the diameter of the pin squared. The axial elasticity inherent to CEFs is a result of the use of small diameter pins (Nele *et al.,* 1994). Pins must be of sufficient diameter, however, to prevent plastic deformation or breakage when subjected to the forces of weight bearing.

Olive or stopper pins have a bead fixed along the midportion of the pin. Olive pins are placed such that the bead is positioned in direct contact with the cortex of the bone. Olive pins significantly improve bending stiffness and stability by minimizing translation of the bone along the pin (Nele *et al.,* 1994). Orbay *et al.* (1992) showed that the use of opposing olive pins effectively mitigated the low-shear resistance associated with pin intersection angles of less than 60^{o} Counter opposed olive pins greatly increased the stability of fixation, particularly in oblique fractures and can be used to generate interfragmentary compression. Calhoun *et al.* (1992) found that parallel, opposing olive pins placed across an oblique osteotomy improved both compressive and distractive stiffness from two to five times as compared with the stiffness provided by the smooth pins placed across the osteotomy.

Circular external skeletal fixation systems

Several circular external skeletal fixation systems have been designed specifically for use in dogs and cats (Ferretti, 1991; Stallings *et al.,* 1998; Marcellin-Little, 1999).

The Jorgensen system has full and partial rings, arches, connecting plates, threaded connecting bolts, spacers and an inexpensive non-calibrated device for tensioning pins. An innovative design feature of the system is the universal joint component (Stallings *et al.,* 1998).

Rings in this system are 70 mm, 100 mm and 150 mm in diameter, made of stainless steel, and less than 3 mm thick, presumably to minimize the frame weight. Unfortunately, these thin rings deform easily during routine use. In addition, the ends of the half rings are not machined with ledges and thus do not interlock in a single plane when attached to one another (Stallings *et al.,* 1998).

The Polyfix systems (Centravet, Tanen, France) were developed by the French veterinarian Yves Latte in 1989 (Stallings *et al.,* 1998; Lewis, 2001). All rings are complete, 5 mm in width and made of anodised aluminium. The Polyfix 4 System, which has 4 mm diameter connecting rods, is designed for use in animals weighing up to 7 kg. The black coloured Polyfix4 rings have an internal diameter of 45 mm. Connecting rods come in 70 mm, 110 mm and 150 mm lengths, and fixation bolts can accept 1.0 mm to 1.4 mm diameter pins. The Polyfix 6 has 6 mm diameter connecting rods and is designed for use in dogs weighing between 7 and 70 kg. The blue-coloured rings are available in internal diameters of 70 mm and 100 mm. Connecting rods come in 80 mm, 120 mm, 160 mm and 200 mm lengths and fixation bolts can accept 1.2 mm to 2 mm diameter pins. The remaining component parts are interchangeable between the two systems, which do not have a tensioning device. These are stable, reliable systems and the small number of components makes them easy to use and economical.

The IMEX CESF (Longview, TX, USA) was first marketed in 1996 (Stallings *et al.,* 1998). Rings in the IMEX system are manufactured from a tempered aluminum alloy, usually reserved for aerospace applications, which imparts strength to the supporting elements without making the fixator too heavy for use in cats and dogs. Full and five-eighths rings, and one-third ring arches are available in four diameters: 50 mm, 66 mm, 84 mm and 118 mm. The IMEX system has an inexpensive non-calibrated device for tensioning pins (Stallings *et al.,* 1998; Lewis *et al.,* 1999a, b).

Hybrid external skeletal fixators

Hybrid external skeletal fixation (HESF) systems are made of a combination of circular and linear ESF systems. They were found to be stiffer than either linear or circular ESF systems (Singh *et al.,* 2007). Farese *et al*. (2002) used an IMEX SK-circular external fixator hybrid constructs for fracture stabilization in dogs and cats, and they found that time to radiographic union ranged from 62 to 137 days. Hybrid fixators were useful constructs for stabilization of humeral and femoral fractures, particularly fractures with short, juxta-articular fracture segments (Kirkby *et al.,* 2008).

Clarke and Carmichael (2006) had used HSEF in treatment of distal diaphyseal fractures of R/U and tibia in three dogs. Hybrid fixator was found to provide more stable fixation of radial and tibial osteotomies as compared to conventional 4-ring circular fixators (Aithal *et al.,* 2007). In another study, pes varus deformity in Dachshunds was corrected by wedge osteotomy of the distal aspect of the tibia stabilized by HESF (Radasch *et al.,* 2008).

Free-form external skeletal fixators

Pins placed in the fracture fragments may be connected with moldable polymers rather than clamps and steel connecting bars. This free-form type of fixation has the advantage that pin direction need not be influenced by the connecting bar location and pin diameter need not be influenced by the clamp size (Tomlinson and Constantinescu, 1991; Roe and Keo, 1997; McCartney, 1998; Worth, 2007). Specific fractures that have been managed with this form of fixation include those of the mandible, the maxilla and the small bones of birds (Chambers, 1981; Stampley and Lawrence, 1993) but the technique was also found effective for treatment of long bone fractures in dogs, small ruminants and calves (Aithal *et al*., 2010; Kumar *et al*., 2011). A number of different compounds have been used to form the connecting bar for free-form fixators. Most are methylmethacrylate based (dental or hoof acrylics or cement used for implantation of prostheses). Epoxy adhesive and various cast materials have been used in birds.

Acrylic external skeletal fixators

Acrylics are polymers which on hardening (polymerization) form a strong structure. In some instances, it is preferable to substitute acrylic (usually polymethylmethacrylate) for the connecting clamps and rods, to complete the external frame (Okrasinski *et al.,* 1991; Willer *et al.,* 1991; Ross and Matthiesen, 1993). Acrylic has been used to substitute for the connecting clamps (McCartney, 1998) and rods, to complete the external frame (Okrasinski *et al.,* 1991; Willer *et al.,* 1991; Ross and Matthiesen 1993).

The use of acrylic columns affords the surgeon greater latitude in fixation pin placement because the fixation pins need not be aligned in a single longitudinal plane. In addition, fixation pins of any diameter may be used, and not just those that can be accommodated by a connecting clamp. Most acrylics (except medical grade polymethylmethacrylate, which usually contains barium sulphate) are radiolucent, which facilitates postoperative assessment of fracture reduction and fracture healing (Lewis *et al.,* 2001).

The acrylic column is also light in weight, which may encourage an earlier return to function (Okrasinski *et al.,* 1991; Egger, 1992; Ross and Matthiesen, 1993). Although the polymethylmethacrylate can be moulded into a cylindrical shape and applied to the fixation pins while in its dough phase, it is preferable to pour or inject the PMMA while in its liquid phase into hollow tubing that has been preplaced over the exposed ends of the fixation pins (Chandy *et al.,* 2007; Julie *et al.,* 2007). Shipov *et al.* (2008) reported that PMMA reinforced with pin within proved to be better than PMMA alone.

Acrylic connecting systems have some limitations. The fumes produced during polymerization are noxious and toxic (Anderson, 1988). Acrylic columns were used for adjunctive stabilization such as in transarticular stabilization following ligamentous reconstruction, and as adjunctive stabilisation of an arthrodesis or fractures that have been reduced via an open reduction primarily stabilised using intramedullary pins, interfragmentary screws and/or cerclage wires (Lewis *et al.,* 2001). Postoperative adjustment or removal of an individual pin is difficult when an acrylic connecting column is used (Ross and Matthiesen, 1993). The column can break, particularly if its diameter is not sufficient (Ross and Matthiesen, 1993).

Acrylic ESF were used in 9 dogs and 2 cats for repair of long bone fractures, for arthrodesis, or for immobilization of joints following ligament or tendon surgery. There were no complications associated with the use of acrylic ESF. Acrylic ESF offers the advantage of reduced cost, improved versatility, and simplified application technique when compared with Kirschner ESF (Okrasinski *et al.,* 1991). In case of long bone fracture treatment, acrylic external skeletal fixators have been used successfully in small animals (Julie *et al.,* 2007; Worth, 2007).

A commercial system (APEF System, Innovative Animal Products, Rochester, MN) has been developed that simplifies the use of acrylic connecting bars for ESF in small animal patients. Based on mechanical evaluations of fixators with acrylic connecting material, suitable-sized bars can be formed for dogs of various sizes (Willer *et al.*, 1991).

Pins with a positive profile end thread and a roughened shaft (Acrylic Half Pins, IMEX Veterinary, Inc, Longview, TX) have been developed to improve the durability of small free-form fixators. The shaft diameter of these pins ranges from 0.9 mm to 2.4 mm. The positive profile end thread is designed to improve engagement in bone. The aim of roughening the pin shaft is to increase the strength of the attachment of the acrylic. This should avoid the need to bend or notch pins (Roe and Keo, 1997).

Epoxy external skeletal fixators

Epoxy is a polymer available in resin form and when mixed with hardener it solidifies to form a very strong material. It is available in the market (non-medical grade) to seal various house-hold items. Due to its mechanical properties and usefulness, it can be used as a component of ESF system just like acrylics.

Epoxy adhesive and cast materials have been used to construct free-form external fixators in birds (MacCoy, 1981; Bennet and Kuzma, 1992; Roe and Keo, 1997). Epoxy putty is easy to handle, inexpensive, and has suitable setting times and mechanical properties (Roe and Keo, 1997).

Recently epoxy fixators have been used for treatment of open fractures in dogs, small ruminants and calves with good success (Kumar, 2007; Aithal *et al.*, 2010). Aithal *et al.* (2009) based on their clinical study reported that epoxy-pin ESF system is strong enough to withstand the weight of small animals weighing up to 100 Kg and can be effectively used to provide rigid fixation, using fixation pins of varied diameter.

Biomechanical studies

Biomechanics is defined as mechanics applied to biology. Mechanics, in turn, is the analysis of any dynamic system, be it the relative motion of quanta and subatomic particles or the motion of galaxies (Smith, 1985). The term mechanics was used as early as 1638 by Galileo describing force, motion, and the strength of materials. (Akeson *et al.*, 1975; Fung, 1981). Biomechanics is the application of mechanical principles to biological systems, such as humans, animals, plants, organs, and cells (Alexander, 2005). One of the best definitions was provided by Herbert Hatze in 1974 was "Biomechanics is the study of the structure and function of biological systems by means of the methods of mechanics". The word biomechanics describes the application of engineering mechanics to biological and medical systems. An understanding of several biomechanical principles is important to understanding the effects that forces have upon biological systems.

Long bone fracture is very common in case of dogs due to extreme force or load. *Force* or *load* is equal to the acceleration of matter (F = mass x acceleration). The amounts of force, the direction of the forces, and the rates of application to the material all have an effect on the outcome of the material. Long bones experience mainly three forces (Smith, 1985), or a combination of these: (i) An *axial compressive force* along the long axis of the bone which is generated by the body weight on that leg; (ii) A *bending force* which is generated by the axial compressive force and by the muscles and tendons around the particular bone and (iii) A twisting or spinning or *torsional force* which is generated by the movement of the bone ends and the joints.

In clinical practice, however, fractures encountered are more commonly a product of a combination of the aforementioned modes. When a load/force is applied, deformation will occur. This can be seen from the load-deformation graph (Fig 1). The stress on the vertical axis is the force per unit area being exerted on/experienced by the bone. The strain on the horizontal axis is the deformation of the bone relative to the stress (Frost, 1971; Black, 1988; Radasch, 1999).

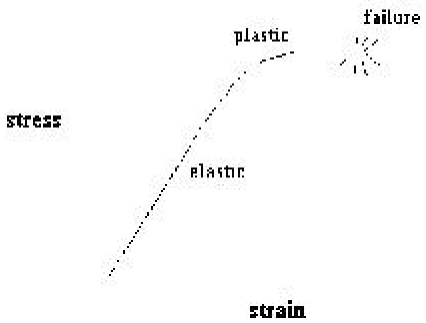

Fig. 1: *A typical stress-strain graph*

Load-deformation curves allow for the mechanical evaluation of a bone or a bone-implant composite. The curves are valuable for obtaining information about how a bone will respond to a force and the effectiveness of implants to resist the applied forces. In particular, the slope of the curve contains information regarding the stiffness, strength, and energy absorption capacity of a material or composite (Frost, 1971; Black, 1988; Radasch, 1999).

The initial phase of a load-deformation curve is the elastic region which is where no permanent deformation occurs in the material. This type of deformation is called *elastic*. In the elastic region the stress and strain are directly (linearly) related to each other. *Stiffness*, which correlates to the elastic region of the curve, is indicated by the amount of load a material can sustain with minimal deformation (Smith, 1985; Hulse and Hyman, 2002). Stiffness is calculated from the slope of the curve; a steeper slope means the stiffness is greater (Frost, 1971; Black, 1988; Radasch, 1999).

When increased loads are applied to the material, permanent deformation occurs starting at the *yield point*. The following region is known as the *nonelastic phase* or *plastic* region. If a load is applied beyond the plastic region, the *ultimate failure point* is reached symbolizing ultimate failure. This is the strength of the material. *Strength* is defined as the amount of load needed to cause catastrophic failure (Frost, 1971; Black, 1988; Radasch, 1999). In the plastic region the strain increases more rapidly than the stress, and failure of course is *fracture*.

Compression

Compression is an **axial force** which causes a shearing stress in the block as indicated by the diagonal arrow (Fig. 2).

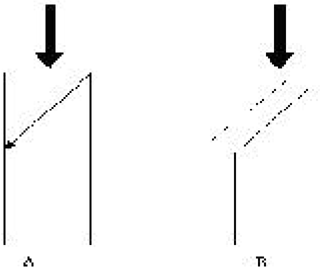

Fig. 2: *Compression forces*

Compression forces on a structure tend to shorten and widen it. Maximal stress occurs on a plane perpendicular to the load applied. If that axial force is sufficiently large the block will break, fail, as shown in, ‘B’ to the right. This is **shear failure**, and when a material fails in a brittle manner because of compression, it fails in shear. This is an important type of failure of bones and in young dogs fracture of growth plate may occur (Smith, 1985; Hulse and Hyman, 2002).

Bending

Long bones are normally subjected to bending which entails compression, tension, and shear. It results in the generation of maximum tensile forces on the convex surface of the bent member and maximum compressive forces on the concave side (Fig. 3). Between the two surfaces, that is, through the cross section of the member, there is a continuous gradient of stress distribution from tension to compression (Smith, 1985; Hulse and Hyman, 2002). An imaginary longitudinal plane corresponding to the transition from tension to compression, approximately in the center and normal to applied force, is designated the *neutral surface*. Along this surface there is theoretically no tensile or compressive load on the material. Another useful designation is the **neutral axis**, which is the line formed by the intersection of the neutral surface with a cross section of the beam, perpendicular to its longitudinal axis.

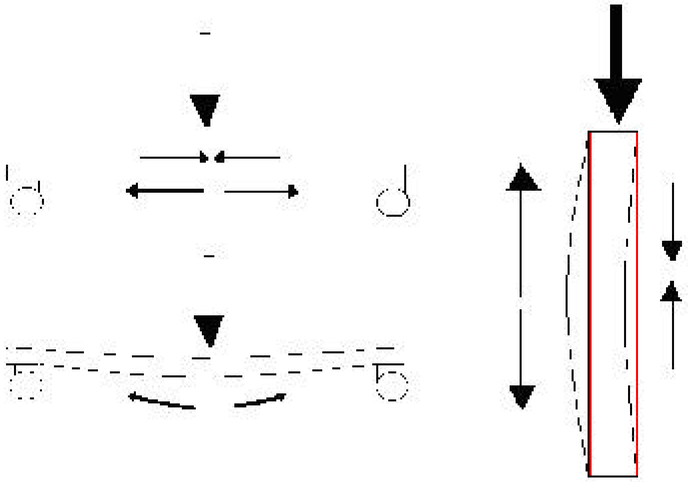

Fig. 3: *Bending force*

The bending may be present because of the angulations of a bone relative to the ground but is largely caused by muscular and tendinous forces exerted on a bone (Smith, 1985).

Under bending load, the beam is bent downward with compression of the upper part and tension of the lower part. Because mature healthy bone is stronger in compression than in tension, failure usually begins on the tension surface (Smith, 1985; Hulse and Hyman, 2002). In very young animals or severely osteoporotic bone, however, folding or buckle fractures are sometimes noted on the concave or compression side of the bone, indicating failure in a compressive mode subsequent to bending (Smith, 1985).

Torsion

The remaining type of simple failure is torsion. Torsional loading as depicted (Fig. 4) is a geometric variation of shear and acts to twist a structure about an axis (the neutral axis). The amount of deformation is measured in terms of shear angle, alpha. As in bending, in which maximum tensile and compressive stresses occur on the surface and distant from the neutral axis, torsional loading produces maximum shear stresses over the entire surface, and these stresses are proportional to the distance from the neutral axis.

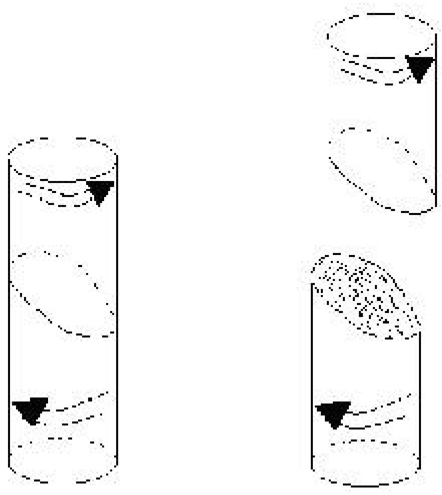

Fig. 4: *Torsional force*

This is an important and almost invariable component of fractures of long bones (Smith, 1985). It probably never occurs alone in fractures of bones. In dog bone subjected to pure torsional loading, it has been suggested that failure begins with crack initiation in a shear mode (Frankel and Nordin, 1980) , that is, parallel to the neutral axis, followed by crack propagation generally along the line of maximum tensile stress (30° to the neutral axis). The net effect of this fracture mechanism is to produce a so-called spiral fracture of the long bone (Smith, 1985; Hulse and Hyman, 2002).

Biomechanics of external skeletal fixators

Various studies have reported the factors which affect the biochemical characters of external skeletal fixators. In case of linear ESF systems, pin number, size and diameter affect the biomechanical stiffness markedly. In addition the diameter and plane occupied by the connecting bar affect the strength of fixator (Chao *et al*., 1979; Egger, 1983; Brinker *et al.,* 1985; White *et al*., 2003).

As compared to the smooth pins, negative profile partially threaded pins are less resistant to bending forces. The thread-smooth shaft interface of partially threaded pins is a stress concentrator, which further compromises the pin's resistance to bending forces and many a times a pin break at this point (Bennett *et al.,* 1987; Palmer and Aron, 1990). Ellis or SCAT (end threaded) pins have comparable axial extraction characteristics as fully threaded pins and similar resistance to bending forces as smooth pins (Bennett *et al.,* 1987). Pins with threads raised above the core diameter of the pin, the positive profile fixation pins, which have stiffness superior to that of negative profile pins (Anderson *et al.,* 1993).

The number of pins in proximal and distal fracture segments has been shown to influence fixator stiffness directly, with three pins per segment yielding 50% to 100% more stiffness in compression, bending, and torsion than two pins per segment (Chao *et al*., 1979). Interestingly, the addition of more pins (more than four) per segment results in an insignificant increase in overall fixator stiffness, particularly in the most critical anteroposterior (AP) bending mode. Pin placement within each pin group is also important. In general, a comparison of various pin numbers used and their placement in bone has demonstrated that fixator stiffness can be improved by increasing pin separation within each group, minimizing pin length, and reducing pin-group separation (Chao *et al*., 1979).

Biomechanical studies performed in the 1980s and early 1990s established the relative strengths and stiffness of various Kirschner-Ehmer constructs (Egger, 1983; Brinker *et al.,* 1985; Bouvy *et al.,* 1993). It was confirmed that uniplanar, unilateral type Ia configurations, particularly those employing double connecting clamps, were significantly weaker than uniplanar, bilateral type II configurations (Egger, 1983; Brinker *et al.,* 1985; White *et al.,2003*). Three-dimensional biplanar type III constructs were biomechanically superior to biplanar, bilateral type II configurations (Egger, 1983, Brinker *et al.,* 1985; White *et al.,* 2003).

Strategies have been developed to improve the biomechanics of type Ia constructs. A second connecting rod can be placed on the fixation pins, which approximately doubles the strength and stiffness of a type Ia construct (Egger, 1983; Brinker *et al.,* 1985).

Modified type I Kirschner-Ehmer constructs, with the most distal fixation pin(s) being (a) full-pin splintage pin(s), have also been biomechanically evaluated and used to stabilize complex distal humeral and femoral fractures (Klause *et al.,* 1990; Dewey *et al.,* 1994; Guerin *et al.,* 1998; Beck and Simpson, 1999).

The bridging of multiple frames with additional bars might also enhance the stiffness of ESF configurations. Although there are reports concerning the biomechanics of pins, the pin bone interface, connecting bars, and frame design, there are few reports in the veterinary literature on the bridging of multiplanar frames within ESFs (Egger, 1983; Lauer *et al*., 2000).

Biomechanical studies of type I fixators showed that addition of the augmentation plates resulted in a 1.9-fold increase in craniocaudal bending stiffness, a 4.2-fold increase in mediolateral bending stiffness and a 4.4-fold increase in axial stiffness (Norris and Kraus, 1999).

Podolsky and Chao (1993) examined the biomechanical properties of circular external fixators and found that factors that increase stiffness in conventional frames also apply to circular frames. In both circular and conventional systems, increased stiffness could be achieved by increasing pin or pin diameter, increasing the distances between the pins or pins, and decreasing the bone to ring or bone to sidebar distance. Features unique to circular frames that increase stiffness include increasing the pin tension and positioning the proper pin-crossing angle.

Circular ESFs are modular systems with numerous component variables that influence the biomechanical behaviour of a particular construct (Ilizarov, 1992). Ring diameter has been shown to be the single most important component variable affecting the biochemical profile (Bronson *et al*., 1998). Comparison of different ring materials showed a 5% improvement in axial and bending stiffness, but no effect on torsional stiffness when using carbon fiber rings (Kummer, 1990). Stainless steel rings were found to be slightly more rigid than carbon fiber rings at low loads (Nele *et al.,* 1994). At high loads (>1437 N), however, stainless steel rings exhibit a typical plastic behavior, with a progressive loss of rigidity. Carbon fiber rings, in contrast, maintained elastic deformability even at high loads.

The axial and torsional rigidity of a single-ring construct has been seen to be directly proportional to the number of pins used in the construct. Single-ring blocks typically use two pins that are placed on opposite surfaces of the ring. Additional pins often referred to as drop pins can be placed on either side of a ring if posts are used. Drop pins also improve resistance to bending forces (Nele *et al.,* 1994). Pin diameter has the most significant influence on torsional stability (Bronson, 1995; Podolsky and Chao, 1993).

Singh *et al.* (2007) conducted an *In vitro* study on biomechanical testing of external skeletal fixation devices (developed using mild steel) for use in large ruminants and found that the hybrid fixator was the most rigid and resilient against compression and bending stresses and was the most suitable fixation device against linear and circular fixators. They were found to be stiffer than either linear or circular ESF systems.

Stainless steel tubes were compared to carbon fiber rods in a study by Kowalski *et al.* (1996); it was found that, during bending, the carbon fiber rods were 15% stiffer than the stainless steel tubes. The stainless steel tubes deformed without breaking when subjected to a 250 Nm bending moment. The carbon rods maintained their elastic stiffness throughout the testing. They concluded that carbon fiber rods were able to sustain higher loads without failing when compared to stainless steel tubes.

Acrylic ESF were compared with Kirschner-Ehmer ESF in biomechanical tests. A 2-cm unilateral acrylic ESF was found to be superior to medium Kirschner-Ehmer ESF in compression and shear loads. Acrylic ESFs when compared with stainless steel counterpart were found to be stronger in axial compression, craniocaudal bending and torsional loads and as strong in mediolateral bending loads (Willer *et al.*, 1991).

The epoxy putties had similar strength, greater apparent modulus, and reduced toughness when compared with the methacrylates (Roe and Keo, 1997). The greater modulus of the epoxy means that an epoxy connected fixator will be stiffer than one connected with methacrylate, if the two fixators have similar frame geometry. The shear strength of the smooth pin interface with the Oatey Epoxy putty was greater than that with the methacrylates (Roe and Keo, 1997). The interface with roughened pins was much stronger than that with smooth pins for all materials tested.

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MATERIALS AND METHODS

The study was carried out in three parts.

Part 1: Development of different designs of acrylic and epoxy-pin ESF systems.
Part 2: *In vitro* biomechanical testing of ESF systems.
Part 3: Clinical evaluation of acrylic and epoxy-pin ESF systems for treatment of long bone fractures in dogs.

Part 1: Development of different designs of acrylic and epoxy-pin external skeletal fixation systems

Fixator constructs were prepared using ultra high density polyethylene (UHDPE) rods (Metalon®- Ashoka steels, Chabri bazaar-Delhi, India) of 20 mm diameter. Length of the two segments of construct was kept 7 cm each. The pins (1.5 mm diameter K-wires) made of 316 L stainless steel (Nebula surgicals Pvt Ltd, Gujarat, India) were passed at two or three points both in proximal and distal segments.

Two types of designs were prepared for compression testing (Fig. 5). In the first design a 2-point fixation per segment of the construct was done and in the second design a 3-point fixation per segment was done. In two point fixation design, the nearer pins (closest to the gap) was passed at 1.5 cm distance from the gap. In both segments, the distance between the pins was kept at 2.0 cm. In three point fixation designs, nearer pin was passed at 1 cm distance from the gap. The distance between the pins in each segment was kept at 2 cm. Pins were passed in the same line, parallel to each other, at a particular distance in uniplanar designs. Pins were crossed in multiplanar-I, multiplanar-II and circular designs at 90° angle taking care that the pins did not interfere with each other. A gap of 5mm (to simulate the unstable fracture

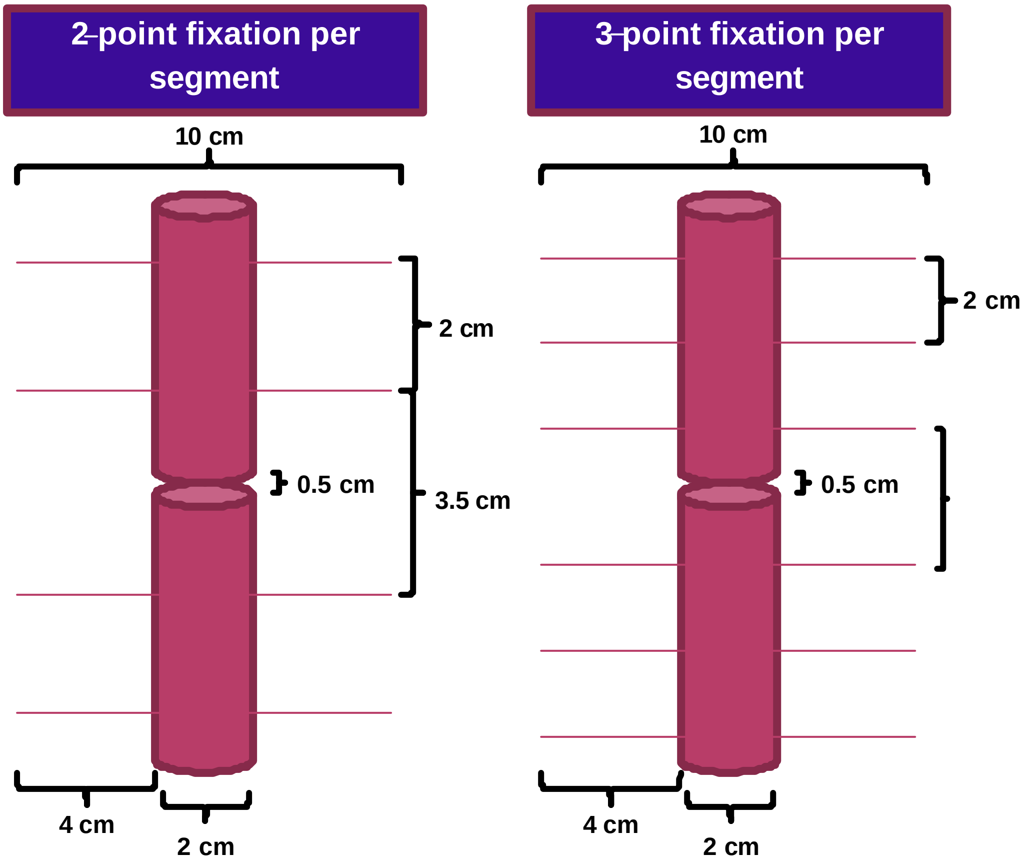


Fig. 5 : *Dimensions of the fixator constructs.*

condition) was kept in between the two segments of UHDPE rods using a piece of plastic for temporary stabilization. The segments were then joined using removable adhesive tape, keeping the segments in proper alignment with respect to the planes of the pins passed. Side bars were constructed at uniform distance of 20 mm from the central UHDPE rod. Total length and diameter of the fixators were 14.5 cm and 10 cm, respectively, including the connecting bars.

Acrylic fixators

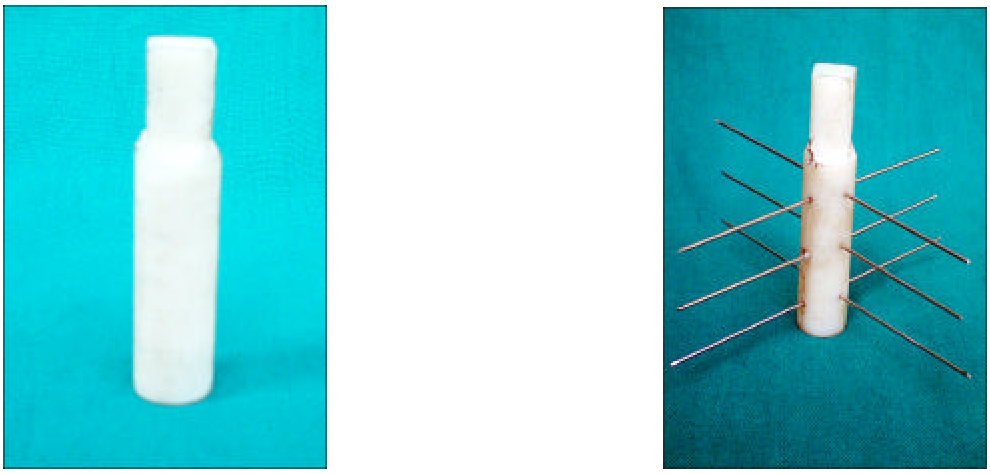
Poly vinyl chloride (PVC) pipes of 20 mm diameter were connected to the pins in the same plane by piercing through and through. The pipes were connected at a fixed distance (20 mm) from the rod. In multiplanar design -II, the crossed pins were connected at the proximal and distal ends using additional pipes of appropriate length. In circular design, the crossed pins were connected at all 4 points at the proximal and distal ends by fixing the pipes in a circular fashion to make rings. Side bars were made separately by passing suitable length pipes into the pins. The side bars and rings were then joined by making an opening in the ring and inserting side bar into it. The point of insertion was then secured with the help of adhesive tape. Thus a temporary scaffold of different designs of fixator constructs was prepared (Fig. 6).

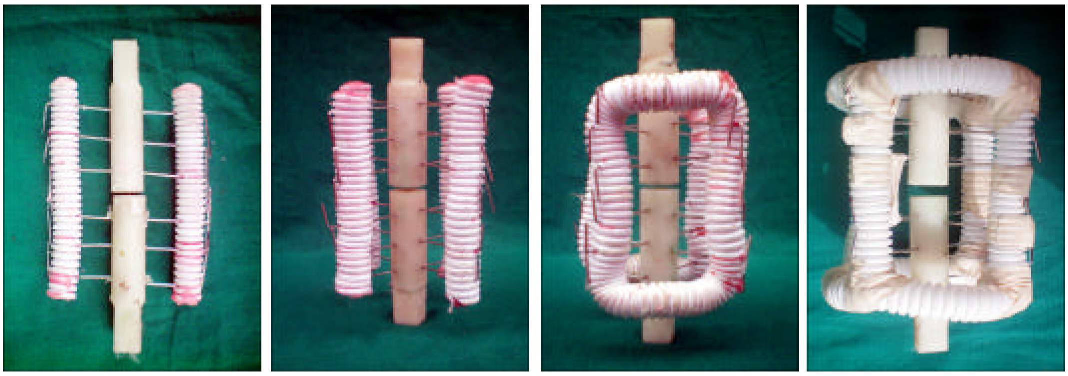
Self curing dental acrylic (Pyrax®-denture base polymer resin, Pyrax polymers-Roorke, India) was used in the present study. Acrylic powder (polymer) and liquid hardener (monomer) were mixed in a glass beaker immediately before application. Acrylic was poured into the side bars in semi liquid state. In circular fixator designs, a small opening was made at the proximal ring and then the acrylic was poured and allowed to flow down the whole scaffold. The open ends of side bars were sealed with the help of adhesive tape. Acrylic was then allowed to polymerize and harden.

Epoxy fixators

The pins in the same plane were bent towards the gap and joined with each other (using adhesive tape) to make a temporary scaffold. Additional pins were used for making frames of multiplanar-II and circular designs. In multiplanar design-II, the pins were joined proximally and distally between the side bars of same plane, so that 2 rectangles were formed on opposite sides. In circular constructs, additional pins were used to make 2 rings, one at the proximal and one at the distal end.

The epoxy-resin (M-Seal® Phataphat, Pidilite Industries Ltd., Daman, India) was mixed with the hardener for 1-2 minutes, till a uniform colour of dough was formed. The side bars of





Uniplanar **Multiplanar-I** **Multiplanar-II** **Circular**

Fig. 6: *Construction of different designs of acrylic fixators.*

the fixator were then constructed by moulding the epoxy on the pins by incorporating the bent pins within the mould. The diameter of the epoxy column was kept uniform at 20 mm throughout. Further, the epoxy was allowed to harden (Fig. 7).

The technical easiness, time required for fixator application, hardening time, weight and cost of the fixator were recorded for different designs of acrylic and epoxy-pin ESF systems.

Weight

Weight of UHDPE rods with the pins was taken as A. The total weight of the fixator construct was taken as B. Weight of filling material (acrylic or epoxy) used (C) was then calculated as :

Weight of filling material (in grams), $C = B - A$

The average weight of each fixator design (n=7) was measured and compared.

Economics

Per unit cost of acrylic and epoxy was calculated. On the basis of material used the cost of filling material (acrylic/epoxy) was calculated as A. The total cost of pins used was calculated as B, depending on the number of pins used in each design by adding the cost of pins and filling material, the total cost (C) of the fixator was calculated as:

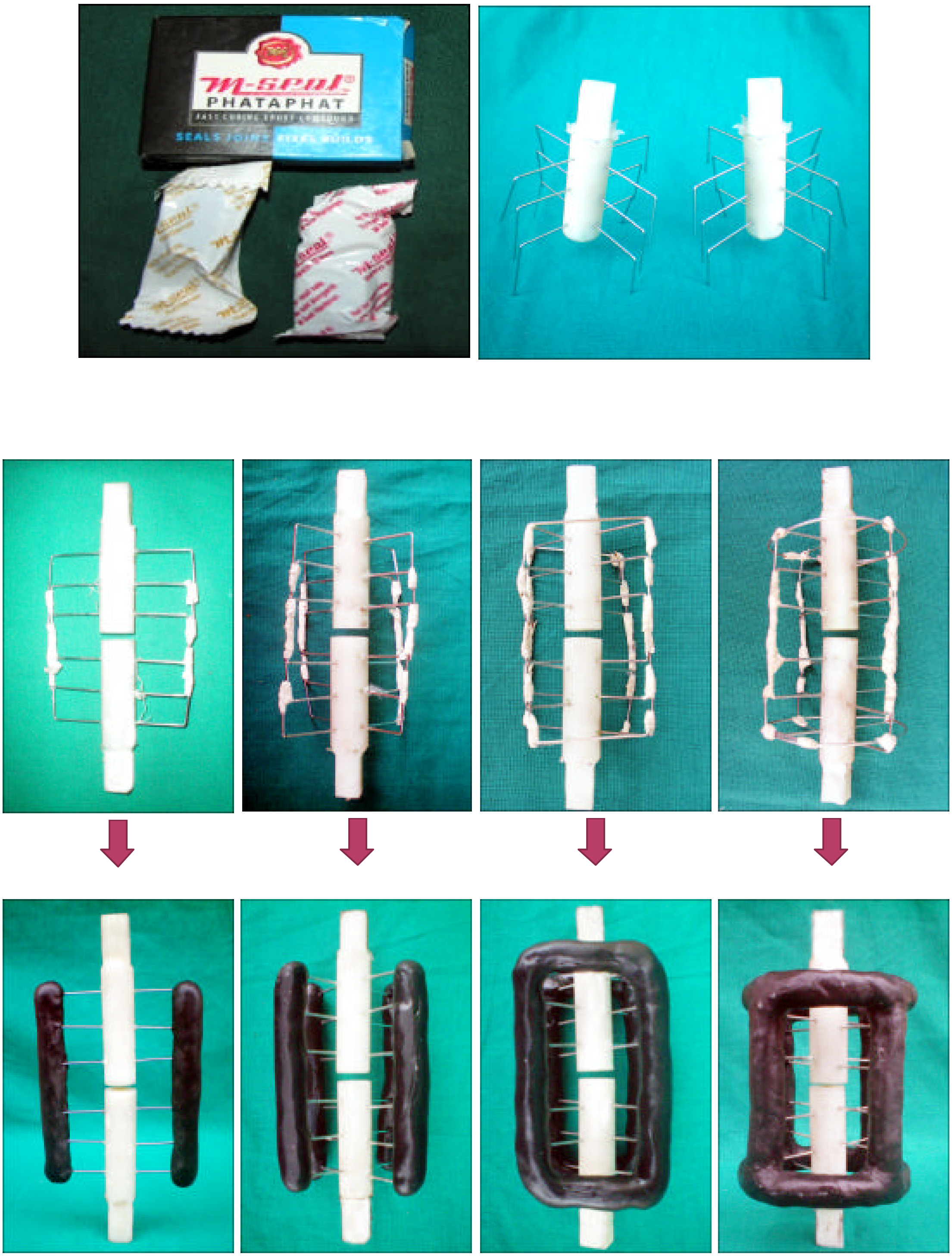
Total cost (in rupees), $C = A + B$

The cost of each design of acrylic or epoxy fixator was calculated and compared.

Part 2: *In vitro* biomechanical testing of external skeletal fixation systems

The biomechanical testing of fixator constructs was done at the Department of Mechanical Engineering, Krishna Institute of Engineering and Technology-Ghaziabad (U.P.).

Fixator constructs of four different designs of acrylic ESF were developed using UHDPE rods as described in Part I, i.e., uniplanar, multiplanar-I, multiplanar-II and circular fixator constructs. Similarly, four different designs of epoxy were constructed i.e., uniplanar, multiplanar-I, multiplanar-II and circular fixator constructs.



Uniplanar **Multiplanar-I** **Multiplanar-II** **Circular**

Fig. 7: *Construction of different designs of epoxy fixators.*

Compression

Compression testing was done on two pin per segment and three pin per segment model constructs (Table 1). The fixator constructs were mounted on Servohydraulic Universal Testing Machine (UTM) and axial load was applied @ 3 mm/min. until failure (Fig. 8). The load deflection graphs were plotted. The maximum force at which failure of the fixator construct occurred was recorded and stress, strain, modulus of elasticity and stiffness of fixator constructs were calculated using various formulae (Rajput, 2006) as described below.

$$\text{Stress } (\text{N/mm}^2) = \frac{\text{Load (Newton)}}{\text{Area } (\text{mm}^2)}$$

$$\text{Strain} = \frac{\text{Change in length (mm)}}{\text{Initial length (mm)}}$$

$$\text{Stiffness (N/mm)} = \frac{\text{Load (Newton)}}{\text{Change in length (mm)}}$$

$$\text{Young's modulus } (\text{N/mm}^2) = \frac{\text{Stress } (\text{N/mm}^2)}{\text{Strain}}$$

Mean ± SE values for different parameters were estimated for different designs of ESF constructs and were compared.

Table 1: *Fixator designs used for compression tests.*

Group	Type of Fixator	Fixator design	Number of samples (2 point fixation model)	Number of samples (3 point fixation model)
A	Acrylic	Uniplanar (AU)	4	4
		Multiplanar-I (AMD-I)	4	4
		Multiplanar-II (AMD-II)	4	4
		Circular (AC)	4	4
E	Epoxy	Uniplanar (EU)	4	4
		Multiplanar-I (EMD-I)	4	4
		Multiplanar-II (EMD-II)	4	4
		Circular (EC)	4	4

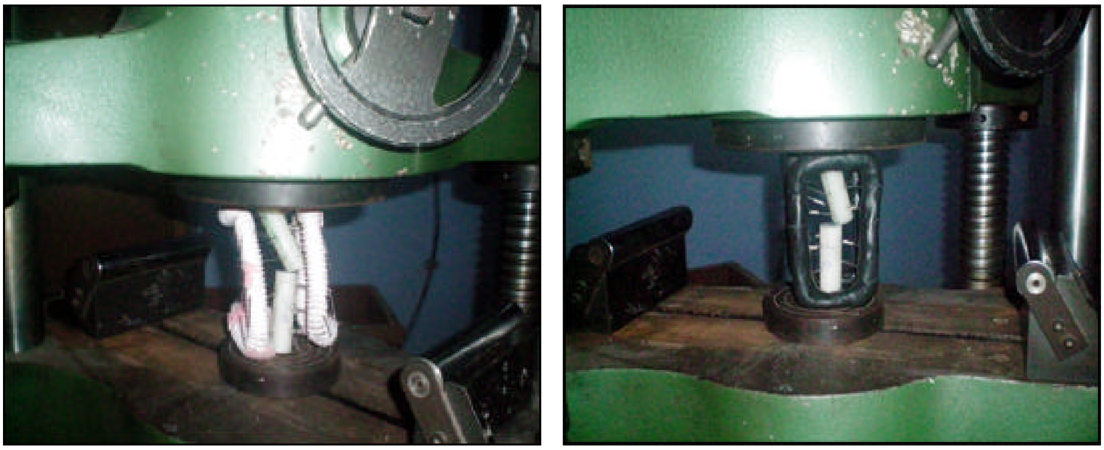


Fig. 8: *Testing of ESF constructs under compression force using UTM.*

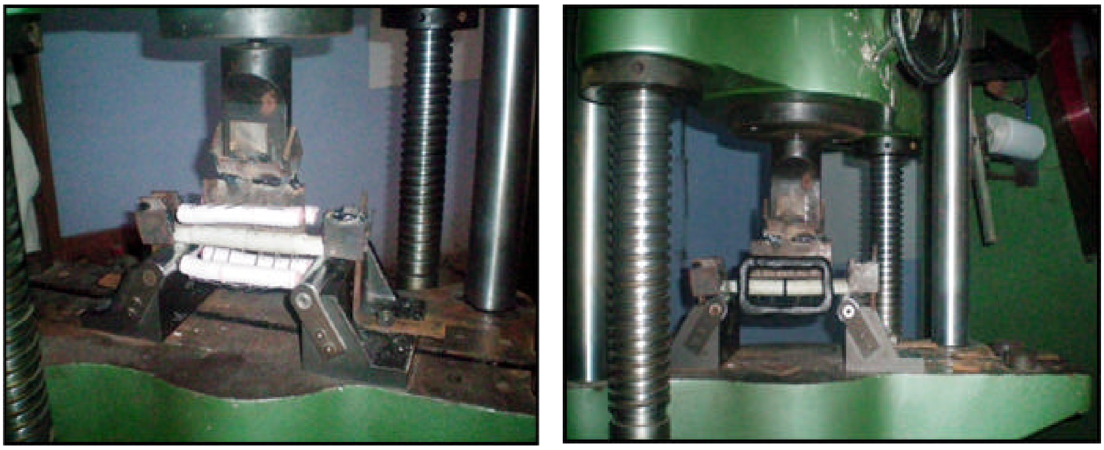


Fig. 9: *Testing of ESF constructs under bending force using UTM.*

Bending

The fixator constructs (3 point support per segment model) were mounted on the bending-test assembly of the UTM (Table 2). They were held in position by specially designed clamps to prevent slipping. The fixator constructs were mounted on the UTM in the form of Simply Supported Beam as shown in fig. 9 and a Uniformly Distributed Load (UDL) was applied @ 3 mm/min up to a deflection of 50 mm. The failure point of the fixator constructs was noted and the load displacement graphs were plotted. Bending moment, modulus of elasticity and stiffness were calculated using the following bending equation (Rajput, 2006).

$$\frac{M}{I}=\frac{\sigma}{Y}=\frac{E}{R}$$

Where M= Bending Moment, I= Moment of Inertia of the section about neutral axis (N.A.), E=Young's modulus of elasticity, R=Radius of curvature of neutral axis and s = Bending Stress.

Table 2: *Fixator designs used for bending and torsion tests.*

Group	Type of Fixator	Fixator design	Number of samples/test	Biomechanical test
A	Acrylic	Uniplanar (AU)	4	Torsion, Bending.
		Multiplanar-I (AM-I)	4	Torsion, Bending.
		Multiplanar-II (AM-II)	4	Torsion, Bending.
		Circular (AC)	4	Torsion, Bending.
E	Epoxy	Uniplanar (EU)	4	Torsion, Bending.
		Multiplanar-I (EM-I)	4	Torsion, Bending.
		Multiplanar-II (EM-II)	4	Torsion, Bending.
		Circular (EC)	4	Torsion, Bending.

Torsion

The fixator constructs (3 point support per segment model) were mounted on the Torsion Testing Machine (0-100 N TTM), with the help of the coupling provided in the machine. One end of the construct was fixed and the other end was rotated. A torque (Nm) was applied

@ 20 degree per minute. The torque and the degree required to fail the constructs were recorded. Shear stress, shear strain and stiffness were calculated using the following equation (Rajput, 2006).

$$\frac{T}{Ip} = \frac{t}{R} = \frac{C\theta}{L}$$

Where T= Maximum Twisting Torque (Nm), Ip= Polar Moment of Inertia (mm^4), t=Shear Stress (N/mm^2), C=Modulus of Rigidity (N/mm^2), ?=Angle of Twist and L= Length of the Shaft.

Part 3: Clinical evaluation of acrylic and epoxy-pin external skeletal fixation systems in fracture treatment

Twenty seven dogs with fractures of the radius-ulna or tibia-fibula reported for the treatment to the Referral Polyclinic, IVRI, Izatnagar (UP), during the period from January 2010 up to March 2011 were used in the study (Table 3).

Table 3: *Design of the clinical evaluation of external fixators.*

Group	Type of Fixator	Sub-group	Bone involved	No. of animals
A	Acrylic ESF	A1	Radius-ulna	7
		A2	Tibia	5
E	Epoxy ESF	E1	Radius-ulna	10
		E2	Tibia	5

Preoperative observations

History

Anamnesis regarding the species, breed, age and sex of the animal, cause of fracture, time since fracture, bone involved and primary treatment given if any, were recorded in each case of fracture. The cases presented were randomly divided in two groups (A and E). Animals of group A were treated with Acrylic ESF and group E were treated with Epoxy ESF. Each group was further divided into two subgroups based on the bone involved.

Clinical examination

All the dogs were examined for the degree of lameness, bone involved, location of the fracture, condition of the wound if any, and soft tissue injury at the fracture site. The degree of soft tissue injury was graded as slight (exposure of bone through a small opening in the skin with little contamination and soft tissue inflammation), moderate (relatively large skin wound with contamination or/and soft tissue inflammation), and severe (very large skin wound with gross contamination, soft tissue inflammation, necrosis, and sometimes with vascular compromise).

Besides these clinical signs, the animals were also examined for different physiological parameters like rectal temperature (RT in °F), respiratory rate (RR- per minute) and heart rate (HR- per minute).

Radiographic examination

The fractured bone was subjected to radiographic examination in the mediolateral and dorsopalmar/plantar or craniocaudal radiographic projections (orthogonal views) to assess the type (transverse/oblique/spiral/comminuted/multiple) and location (proximal third/ middle third/distal third of diaphysis) of fracture.

Intraoperative observations

In open fractures, after shaving and cleaning the site around the wound, the wound at the fracture site was thoroughly washed with normal saline and antiseptic solution containing 1% povidone iodine. The fracture site was immobilized temporarily by application of splint and bandage, to avoid further trauma to the bone and soft tissue, till the time of surgical fixation of fracture fragments. Antibiotic Taximax (Cefotaxim +Sulbactum @ 25 mg/kg body weight) and anti inflammatory-analgesic drugs (Meloxicam @ 0.2 mg/kg body weight) were administered to all the animals, till the day of surgery.

Food was withheld for 12 hr and water for 6 hr prior to surgery. The whole length of the bone (in case of diaphyseal fractures) including the adjoining bones (in case of metaphyseal/ epiphyseal fractures for trans-articular fixation) was clipped, shaved and prepared for aseptic surgery. All the animals were given broad-spectrum /sensitive antibiotic (Taximax @ 25 mg/kg i.v.) and anti inflammatory-analgesic drugs (meloxicam @ 0.2 mg/kg i.v.) before the start of the surgery. Fracture reduction and fixation was done under general anaesthesia using atropine @ 0.04 mg/kg i.m., diazepam @ 0.5 mg/kg i.v. and pentazocine @ 1 mg/kg i.v. as pre anaesthetics and 5 % thiopentone sodium administered i.v. till effect for induction and maintenance of anaesthesia.

After restraining the animal, the site was scrubbed and painted with 2% povidone iodine solution. Fracture reduction was done by closed or semi-open method. Subsequently, by keeping the bone fragments in alignment, the pins (K-wires) were passed. While introducing the pins, an attempt was made to avoid injury to major vessels, nerves and muscular attachments by introducing the pins by hand through the soft tissues up to the level of bone (most vessels and nerves were gently pushed aside by this method). The pins were inserted through bone using a low speed (200 rpm) electric drill with continuous dropping of cold sterile normal saline solution to reduce thermal necrosis. The first pin was passed in the smaller fragment, followed by others, one by one alternatively in both segments. The pins were directed perpendicular to the long axis of the bone, from caudomedial to craniolateral and from craniomedial to caudolateral direction. The pins were crossed with each other at an angle of 70° to 90° in such a way that they did not interfere with each other in the medullary cavity. In case of trans-articular fixation for the fractures at the distal end of R/U or T/F, single mediolateral pins were inserted in the metacarpals/metatarsals. In general, 1.5 mm K-wires were used in radius/ulna and tibia/fibula, whereas in metacarpals and metatarsals, 1.2 mm K-wires were used. Multiplanar design-II was used in all cases. A hybrid of multiplanar-II and uniplanar designs was used in the cases where fracture was near the joint.

For acrylic fixator, after passing the pins, 20 mm diameter corrugated mouldable PVC pipe of desired length was passed through the pins to construct the side bars (Fig. 10A). Acrylic powder was mixed with liquid in pre-cooled glass beaker in the ratio of 2:1. The mixture was made immediately before filling into the hollow pipes. The liquid was then poured into the pipes with their cut/open ends facing upwards. Open ends of pipe were joined by cutting a small triangular piece from one end of the pipe so that the two ends of the pipe could fit into each other. This joint was then secured with the help of an adhesive tape. To prevent damage to the skin during polymerization, crushed ice was kept in between the fixator columns and the skin. The acrylic columns were then allowed to harden; subsequently the remaining ice was removed.

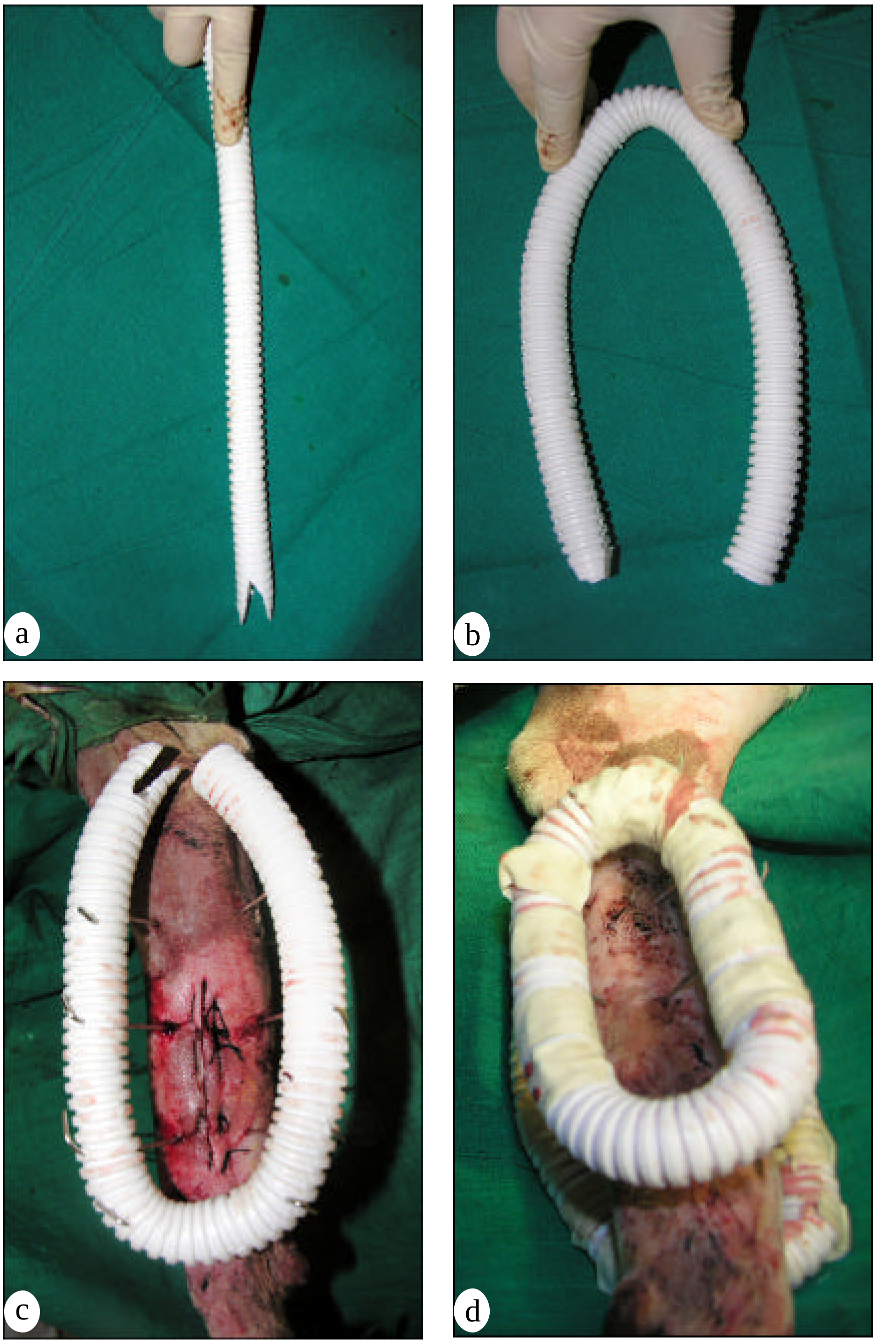


Fig. 10A: *Surgical fixation of fracutre with acrylic ESF using semiopen method;* a) Triangular piece of PVC pipe cut at ends; b) PVC pipe is moulded into the desired shape; c) Pipe is passed through the pins to form temporary scaffold; d) Acrylic is poured and ends sealed.

For epoxy fixator, after passing the pins, the pins in the same plane were bent at 2 cm from the skin towards the facture site (Fig. 10B). The bent pins were then joined with the help of adhesive tape to form a temporary scaffold. Using additional pin pieces, the two side bars of each side were joined at the proximal and distal ends. The epoxy hardener and resin were then mixed thoroughly. About 1-2 minute mixing was required to make dough which was of uniform colour. The epoxy putty was then hand moulded and applied along the temporary scaffold incorporating the bent pins within the mould making a near uniform side bars of appropriate diameter (15 to 20 mm). The epoxy fixator so formed was then allowed to harden.

Intraoperatively, the time required for fracture reduction was recorded. The number of pins passed through the bone fragments, the diameter and the direction of pins used, and the distance between the skin and side bars was recorded in each case. The diameter of the acrylic/epoxy columns was noted. The technical easiness/difficulties during the application of fixators and the degree of fracture stability achieved at the time of fixation were assessed subjectively and graded as very good, good and satisfactory. In addition, the time required for passing the pins, to apply fixator and for hardening was recorded. Complications, if any, observed during the time of application of fixator were also noted.

Postoperative observations

Postoperative care and management

Anti-inflammatory-analgesic drug, meloxicam @ 0.2 mg/kg, was administered IM on the day of surgery, subsequently oral administration was advised for 3-5 days. Broad spectrum antibiotic taximax, @ 25 mg/kg i.m., was administered for a minimum of 3-5 days. Regular cleaning and dressing of the wound was done with 1% povidone iodine solution. The pins-skin interfaces were also cleaned regularly. All the animals were observed until the fracture healed radiographically and the fixator was removed.

Clinical observations

Wound healing: The status of wound was assessed regularly and the total time required for wound healing was recorded in cases of open fractures and open fracture reduction cases.

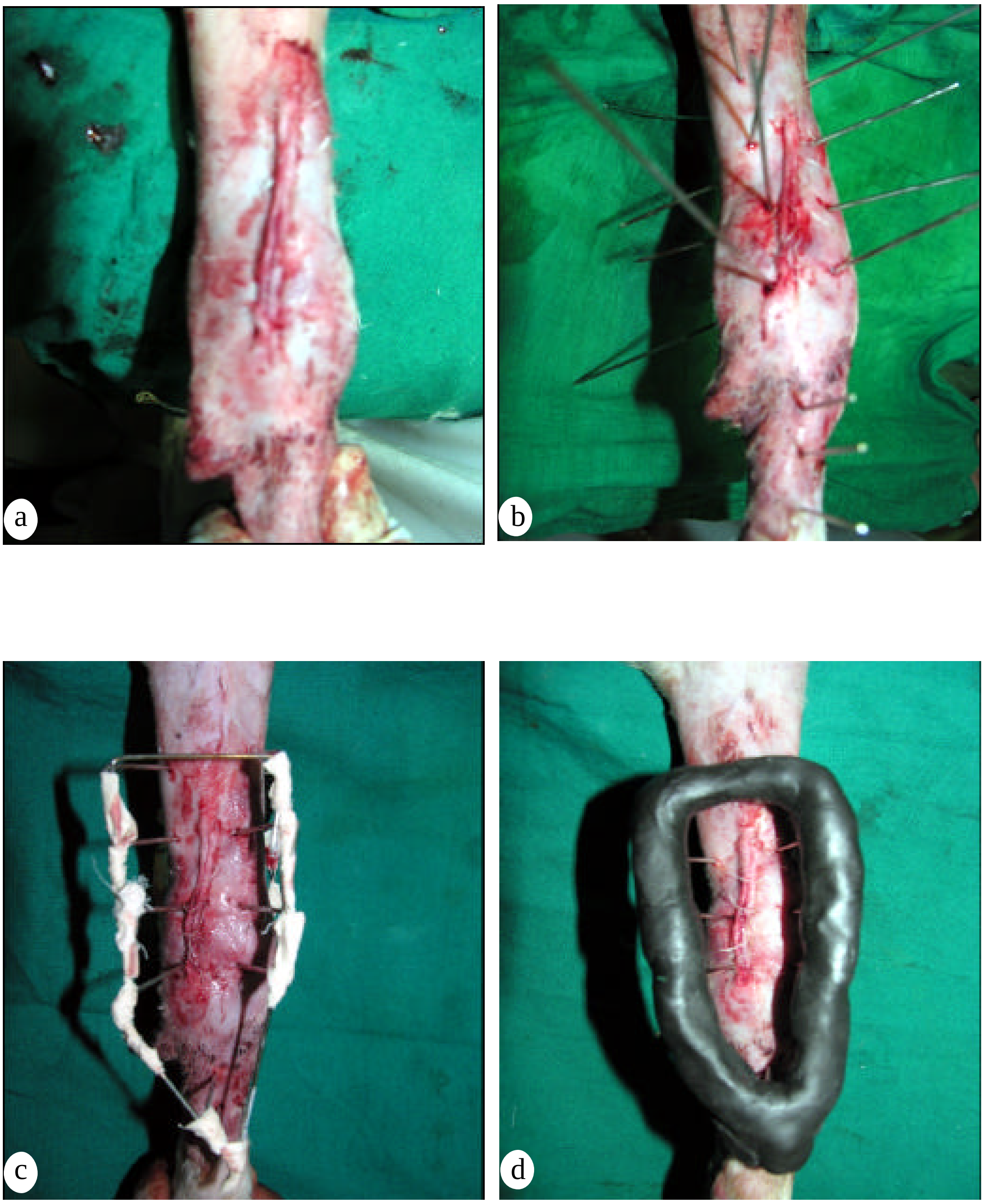


Fig. 10B: *Surgical fixation of fracutre with epoxy ESF;* a) Fracture reduction by semiopen method; b) Pins passed through the skin and bone; c) Pins bent and joined to form temporary scaffold; d) Epoxy putty applied.

Status of the fixation device: The status of the fixation device (including different components like pins and side bars) was evaluated regularly for any change in the position or deformation.

Pin tract sepsis: The pin-skin interfaces were regularly watched for the presence of any discharge, infection etc. The degree of discharge, sepsis was recorded in each of the pin tracts and graded as: 1-slight = the pin-skin interface is moist with slight oozing of serous/ fibrinous exudate on pressing, 2-moderate = seropurulent exudation from the point of pin insertion on pressing the site, and 3-severe = spontaneous exudation or excessive exudation on pressing (Kumar *et al.,* 2011).

Gait analysis: For analysis of gait, the animals were evaluated while standing, walking and running to observe weight bearing on the affected limb. The animals were observed on days 3, 7, 15, 30 and 45 postoperatively. Various scores were given for standing, walking and running as detailed below:

1- no weight bearing, 2- slight weight bearing (animal mostly keeps the limb lifted and keeps down i.e., limb lifted mostly), 3: moderate weight bearing (keeps the limb on ground but lifted in between i.e., limb kept on ground mostly), and 4: full/good weight bearing (touches the limb on the ground during each step with full weight bearing).

Microbiological examination

The samples for microbiological examination were collected from the wound site and pin-skin interfaces at different intervals. The antibiotic sensitivity test was then performed and the antibiotics were chosen for parenteral administration, if required.

Haemato-biochemical observations

About 2mL of the venous blood was collected in heparinized syringe on days 0, 3, 7, 30 and 45 for haemato-biochemical examination. Haemoglobin (Hb-g/L) was estimated by using 0.1 N HCl with the help of Sahli's haemoglobinometer, and packed cell volume (PCV-%) was estimated using microhaematocrit method. Plasma was separated from the remaining blood, which was used for the estimation of alkaline phosphatase (Units/L) by pNPP-AMP method, calcium (mmol/L) by O-Cresolphthalein Complexone end point assay, and phosphorus (mmol/L) by UV Molybdate end point assay.

Radiographic observations

Orthogonal radiographs were taken immediately after the application of fixator to assess the level of fracture reduction, alignment of bone fragments and the placement of pins through the bone. Radiographs were also taken after the application of fixator, i.e. on days 15, 30, 45 and 60, to evaluate the status of fixation, fixator components, fracture healing and complications, if any. Once the fracture healing was evident on radiographic examination (bridging callus), the fixator was removed.

Fixator removal : After the radiographic healing, the fixator was removed by cutting the pins with a pin cutter. The cut pins were then pulled out with the help of a plier. Pin tracts were cleaned and flushed with povidone iodine and then bandaged. Owners were advised to regularly clean and dress the pin tracts. Movement of the animals was restricted up to one week. Oral administration of analgesic, meloxicam @ 0.2 mg/kg body weight, was advised for 2-3 days after fixator removal.

Functional recovery

Functional recovery of the animal was graded as: very good - normal fracture healing with normal limb usage; good - normal fracture healing but slight lameness persisting; satisfactory - fracture healing with slight mal union/delayed union leading to apparent lameness and unsatisfactory-fracture failed to heal due to fixation failure or infection (Kumar *et al.,* 2011).

Statistical analysis

The data on clinical, haemato-biochemical and biomechanical parameters were analyzed by Analysis of Variance (ANOVA) and Duncan’s Multiple Range Test (DMRT) to compare the values with their respective base values within a group and at corresponding intervals between groups. For non-parametric observations Kruskal-Wallis and Mann-Whitney test was used (Snedecor and Cochran, 1994).

❑❑❑

RESULTS

Part 1: Development of different designs of acrylic and epoxy-pin external skeletal fixation systems.

The technical easiness, time required for the fixator application, hardening time (of acrylic and epoxy), weight and cost of the fixator were recorded for different designs of acrylic and epoxy-pin ESF systems (Table 4).

Construction of fixator models was comparatively easier and less time consuming for epoxy fixators than acrylic fixator models. Handling of acrylic was comparatively difficult because of its liquid phase, whereas the doughy consistency of epoxy putty facilitated its handling. Fixing pipes through the pins at proper distance was comparatively difficult, especially in circular designs. It took significantly more time for construction of acrylic circular design, in which acrylic had to be filled. While pouring the acrylic into the pipe, leakage occurred in many fixator constructs at the pipe-pin interfaces or at pipe junctions. During mixing of acrylic powder with the liquid, noxious fumes were produced, which caused irritation to the eyes, respiratory system and skin. In addition the heat produced during hardening of the acrylic made difficulty in handling the models during construction. There was slight expansion of the acrylic while hardening. At lower room temperature the hardening of acrylic was slower as compared to that at higher temperatures. Hardening time was less for acrylic (nearly 11 min), so once set it did not give any chance for even slight adjustments. There was no fume and negligible heat production during processing of epoxy putty. The time for hardening (22 min) was comparatively more with epoxy, which allowed minor adjustments in alignment of segments even after pin fixation.

Table 4: *Comparison of acrylic and epoxy based on their physical characters.*

Parameters	Acrylic	Epoxy
Fumes	Yes	No
State	Liquid	Doughy
Relative handling	Difficult	Easy
Leakage while applying	Possible	No
Heat/exothermic reaction	More	Less
Time for hardening	Less	More
Relative weight	Less	More
Relative cost	More	Less
Radiographically	Translucent	Opaque

Weight

The weight of filling material, acrylic, was significantly (P<0.05) lesser than that of epoxy material (Fig. 11).

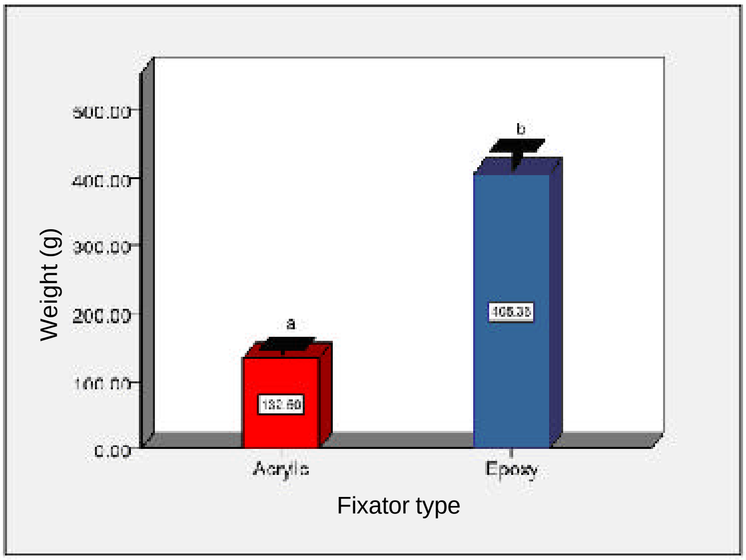


Fig 11: *Mean ± SE of weight (g) of the filling material in acrylic and epoxy fixators.*

The weight of filling material was the least in uniplanar designs, followed by multiplanar-I, multiplanar-II and circular designs, in the increasing order (Fig. 12). The weight of epoxy was significantly (P<0.05) more than the acrylic in corresponding designs.

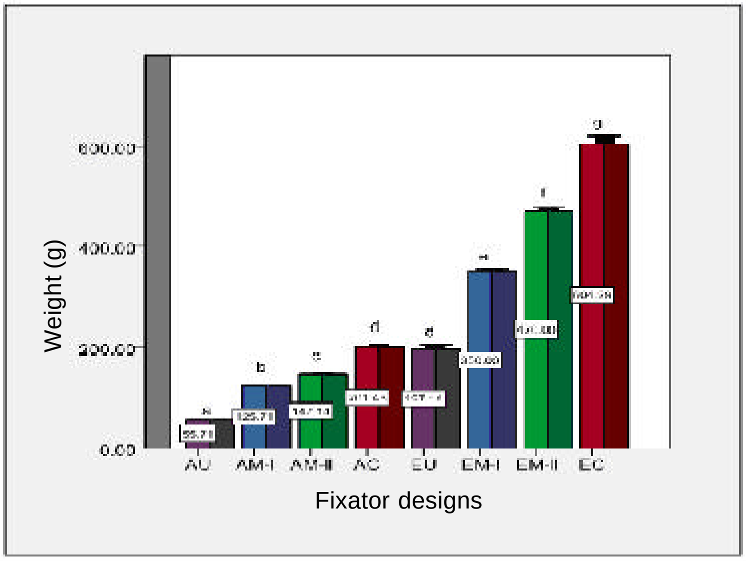


Fig 12: *Mean ± SE of weight (g) of the filling material in different designs of acrylic and epoxy fixators.*

The total weight of the epoxy fixators was significantly higher than acrylic fixators (Fig. 13).

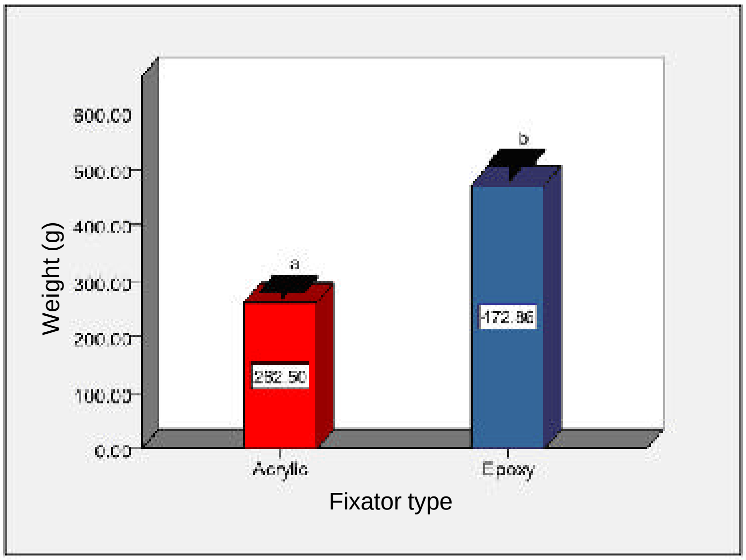


Fig 13: *Mean ± SE values total weight (g) of the acrylic and epoxy fixators.*

The mean ± SE values of the total weight of different designs of fixators was significantly (P<0.05) different from each other with uniplanar designs weighing the least, followed by multiplanar-I, multiplanar-II and circular designs (Fig. 14). Different designs of epoxy fixators weighed significantly (P<0.05) more than their corresponding acrylic fixator designs.

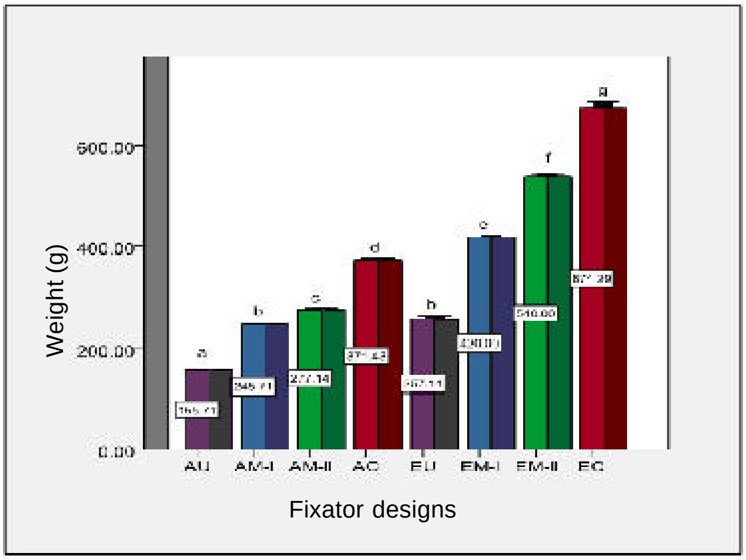


Fig 14: *Mean ± SE of total weight (g) of different designs of acrylic and epoxy fixators.*

Economics

The mean ± SE of the cost of filling material (acrylic and epoxy) used has been shown in fig. 15. Overall, the cost of acrylic material per unit fixator was about ` 254.00, whereas it was about ` 83.00 for epoxy material per unit fixator.

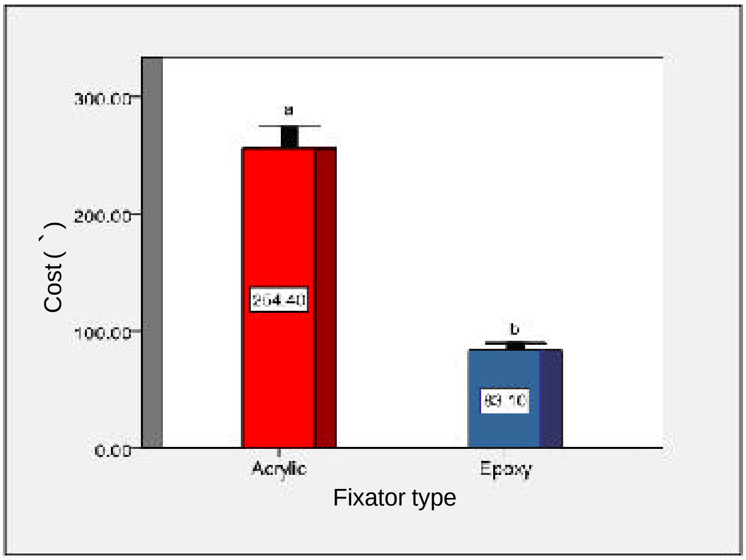


Fig 15: *Mean ± SE of cost (`) of the filling material in acrylic and epoxy fixators.*

The cost of epoxy material required to develop different designs was significantly (P<0.05) lesser than the acrylic material for corresponding fixator designs (Fig. 16).

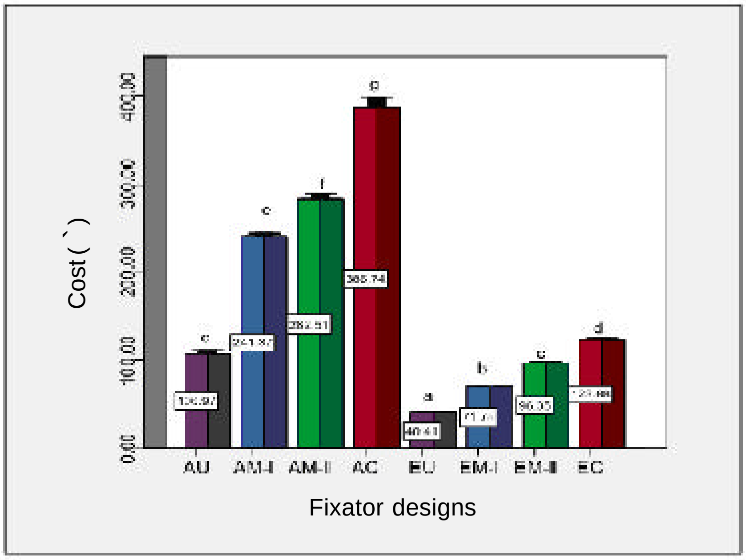


Fig 16: *Mean ± SE of cost (`) of the filling material in different designs of acrylic and epoxy fixators.*

The total cost of the individual acrylic fixator design was significantly more (P<0.01) than the corresponding epoxy fixator design (Fig. 17).

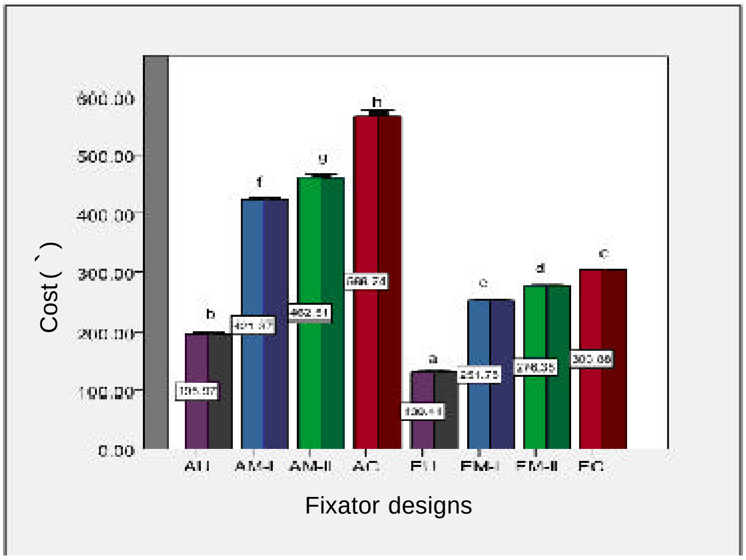


***Fig 17:** Mean ± SE of total cost (`) of the different designs of acrylic and epoxy fixators.*

The overall total cost of the acrylic fixator per unit was ` 412.00, which was significantly (P<0.05) higher than that of epoxy fixator, which was ` 241.00 (Fig. 18).

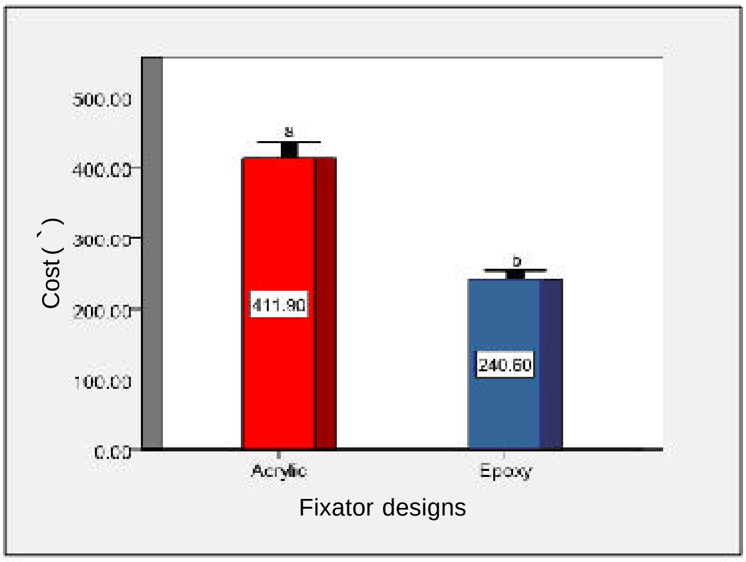


***Fig 18:** Mean ± SE of total cost (`) of the acrylic and epoxy fixators.*

Time

The average time required for application of epoxy fixators was 13.6 min, which was significantly (P<0.01) lesser than for acrylic fixators which took about 20 min (Fig. 19).

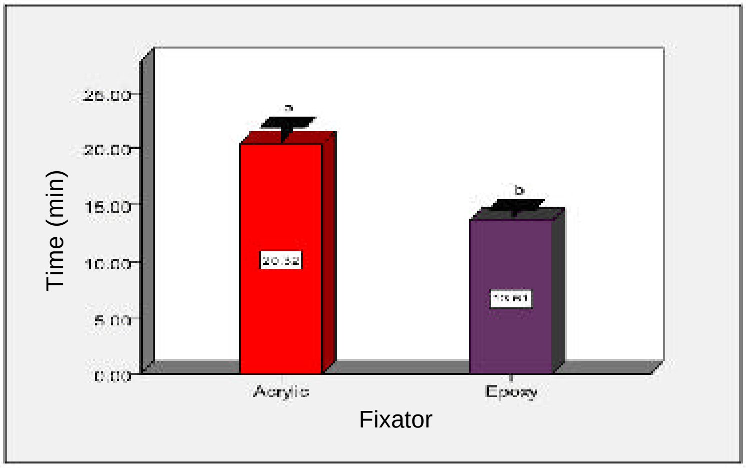


Fig 19: *Mean ± SE of time (mn) for application of acrylic and epoxy fixators.*

The time required for application of circular fixator designs was significantly more (P<0.05) than the multiplanar designs. There was no significant (P>0.05) difference between multiplanar design-I and II. Uniplanar designs took significantly (P<0.05) lesser time for their construction than any other fixator design (Fig. 20).

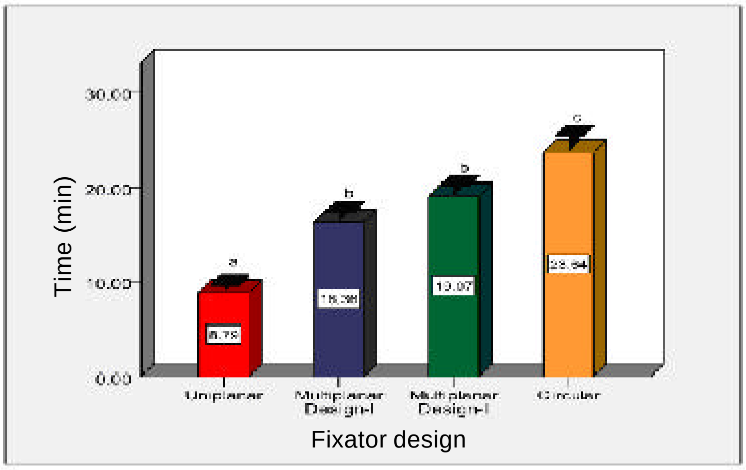


Fig 20: *Mean ± SE of time (min) for application of different designs of fixators.*

Acrylic circular design took nearly 30 min for its construction, which was significantly (P<0.05) more than all the other designs of acrylic or epoxy fixators. Acrylic multiplanar design-II took significantly (P<0.05) more time than acrylic multiplanar design-I and even epoxy circular design. Epoxy circular and multiplanar design-II took almost equal time for their construction, which was significantly (P<0.05) more than required for epoxy multiplanar design-I. Epoxy uniplanar design took least time for construction (7 min), which was significantly (P<0.05) lesser than the acrylic uniplanar design (Fig. 21).

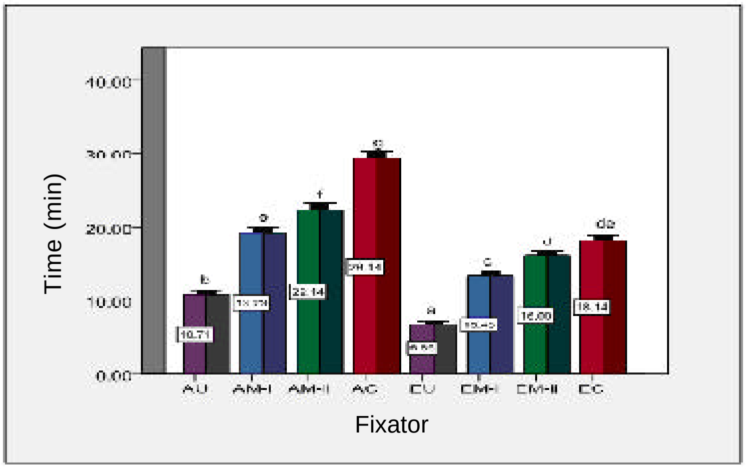


***Fig 21:** Mean ± SE of time (min) for application of different designs of acrylic and epoxy fixators.*

The time required for hardening/setting was lesser for acrylic constructs (11 min) than epoxy constructs (22 min). Thus the total time required for application of epoxy and acrylic fixators did not differ significantly (P>0.05).

Part II: *In vitro* biomechanical testing of different designs of acrylic and epoxy-pin external skeletal fixation systems

Compression

Compression testing was done in both 2-point fixation constructs and 3-point fixation constructs.

Two-point fixation constructs

In general, strain followed the trend opposite to that of stress, stiffness and modulus of elasticity. No significant (P>0.05) difference was recorded in stress and strain values between the ESF constructs having 8 and 4 pins (Figs. 22 and 23).

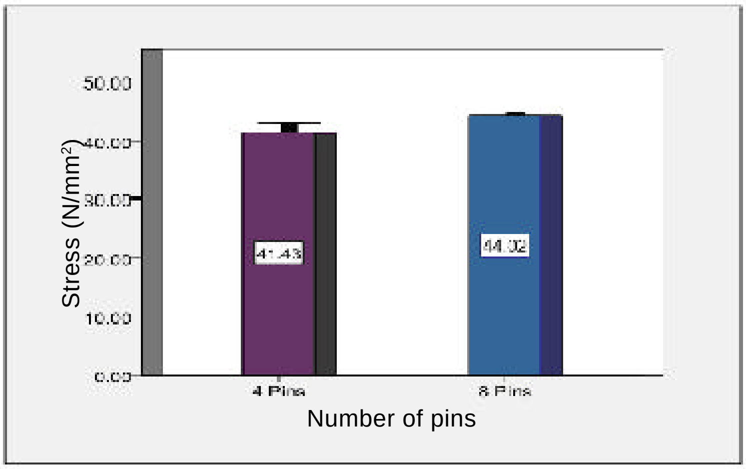


***Fig. 22:** Mean ± SE values of stress in the fixators having 4 or 8 pins.*

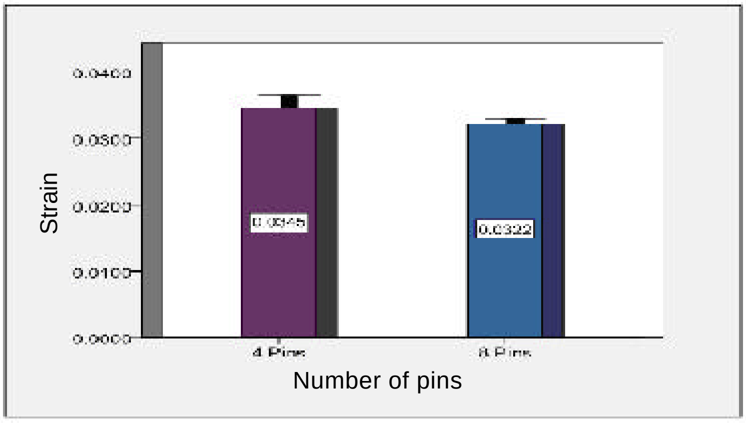


Fig. 23: *Mean ± SE values of strain in the fixators having 4 or 8 pins.*

The mean ± SE values of stiffness and modulus of elasticity were significantly (P<0.05) higher for ESF constructs having 8 pins (multiplanar/circular designs) than for 4 pins (uniplanar) as shown in figs. 24 and 25.

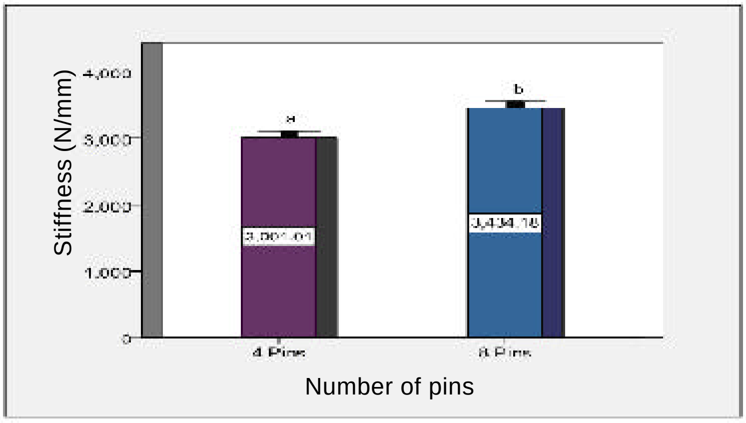


Fig. 24: *Mean ± SE values of stiffness in the fixators having 4 or 8 pins.*

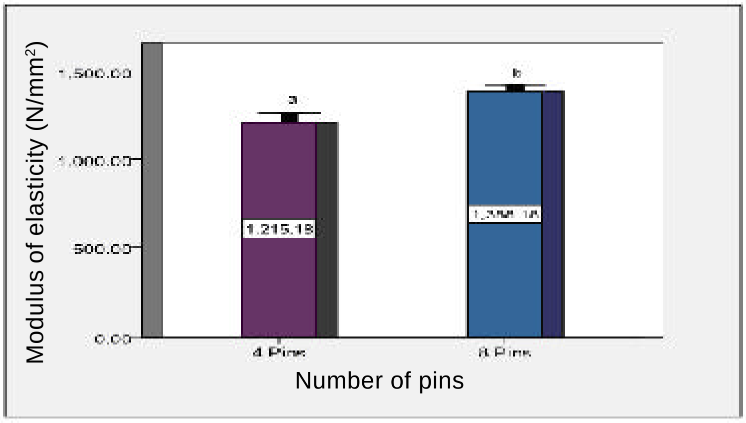


Fig. 25: *Mean ± SE values of modulus of elasticity in the fixators having 4 or 8 pins.*

A significantly (P<0.05) higher value of stress was recorded for epoxy fixators than acrylic fixators (Fig. 26).

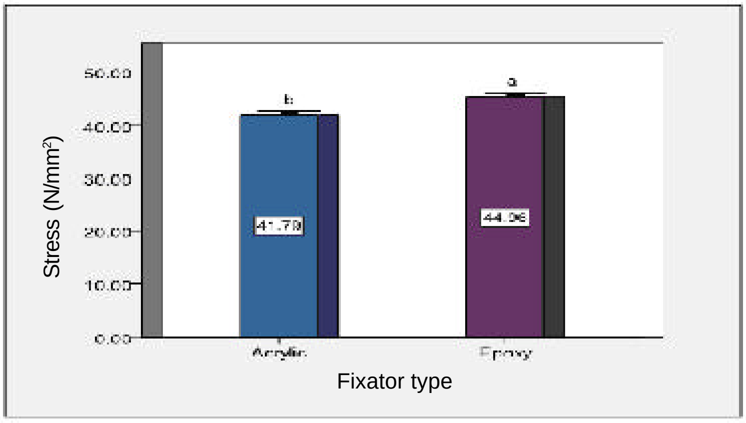


Fig. 26: *Mean ± SE values of stress in acrylic and epoxy fixators.*

However, no significant (P>0.05) difference was recorded in the values of strain, stiffness and modulus of elasticity between acrylic and epoxy fixators (Figs. 27, 28 and 29).

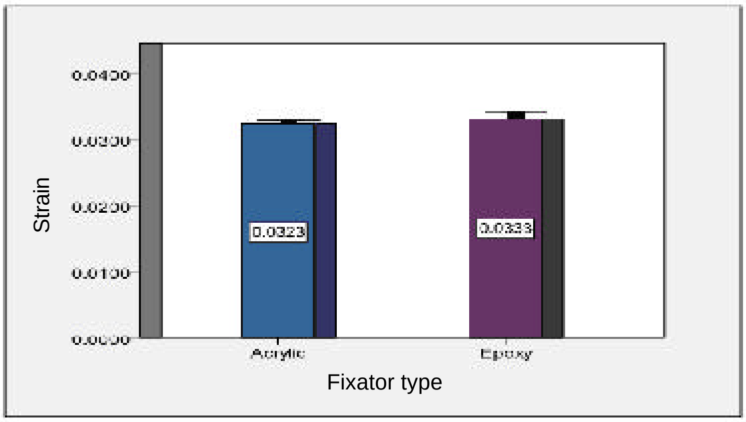


Fig. 27: *Mean ± SE values of strain in acrylic and epoxy fixators.*

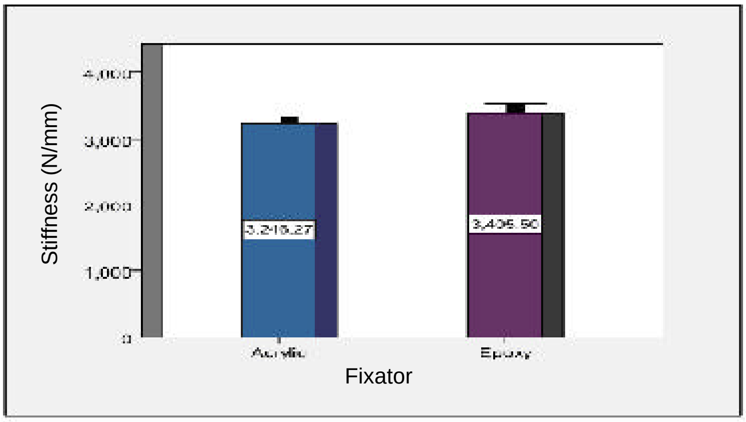


Fig. 28: *Mean ± SE values of stiffness in acrylic and epoxy fixators.*

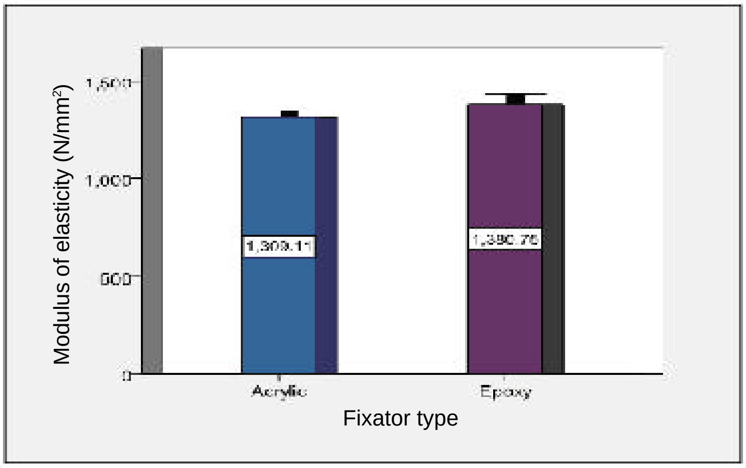


Fig. 29: *Mean ± SE values of modulus of elasticity in acrylic and epoxy fixators.*

There was no significant (P>0.05) difference in the stress and strain values between different designs of fixators (Figs. 30 and 31).

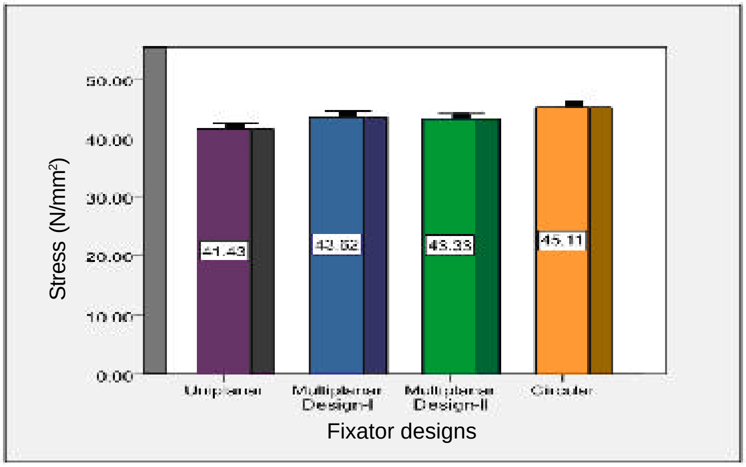


Fig. 30: *Mean ± SE values of stress in different designs of fixators.*

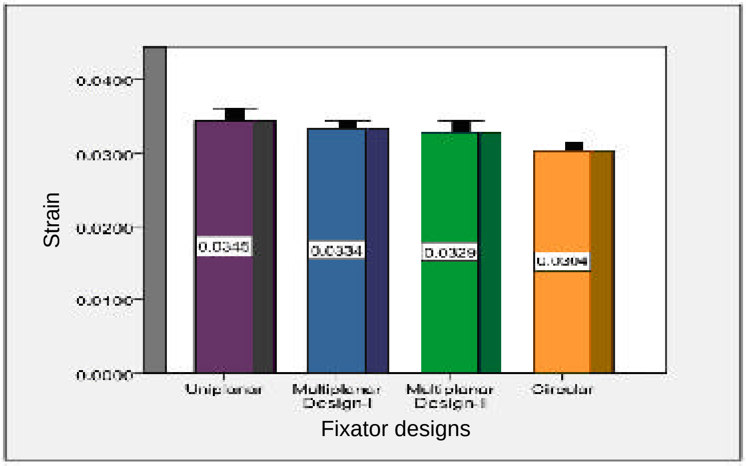


Fig. 31: *Mean ± SE values of strain in different designs of fixators.*

Stiffness of circular design fixation systems was non significantly (P>0.05) higher than multiplanar design-II, but it was significantly (P<0.05) higher than other fixator designs (Fig. 32).

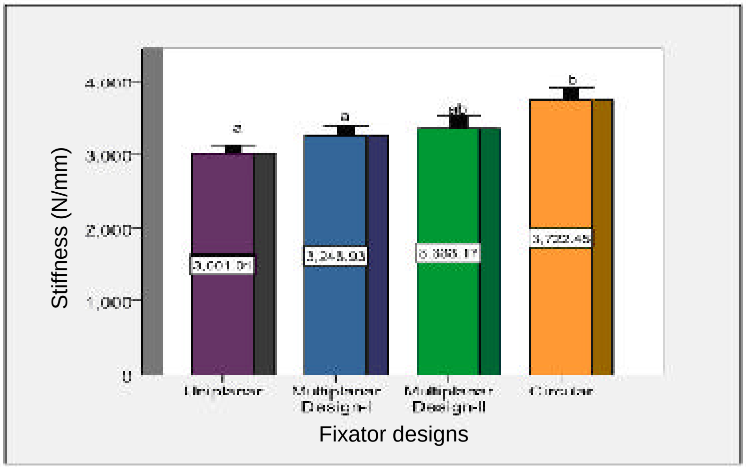


Fig. 32: *Mean ± SE values of stiffness in different designs of fixators.*

Modulus of elasticity in uniplanar fixator design was significantly (P<0.05) lower than circular design, however, no significant (P>0.05) difference was recorded between multiplanar and circular designs (Fig. 33).

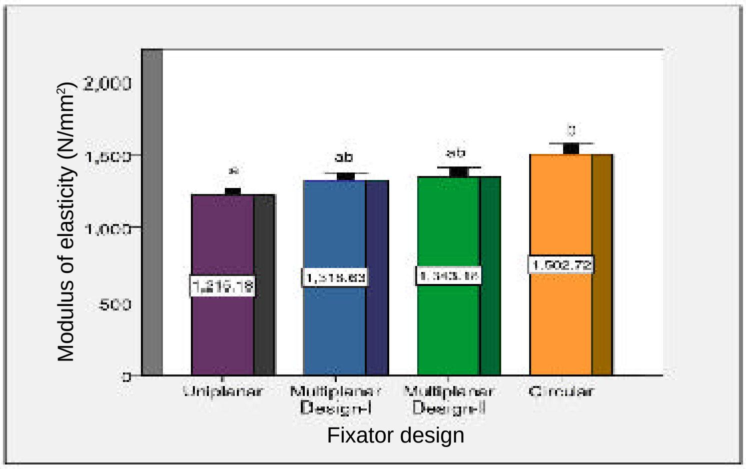


Fig. 33: *Mean ± SE values of modulus of elasticity in different designs of fixators.*

There was no significant (P>0.05) difference in the values of stress, strain, stiffness and modulus of elasticity between acrylic and epoxy fixators of a particular design (Figs. 34, 35, 36 and 37).

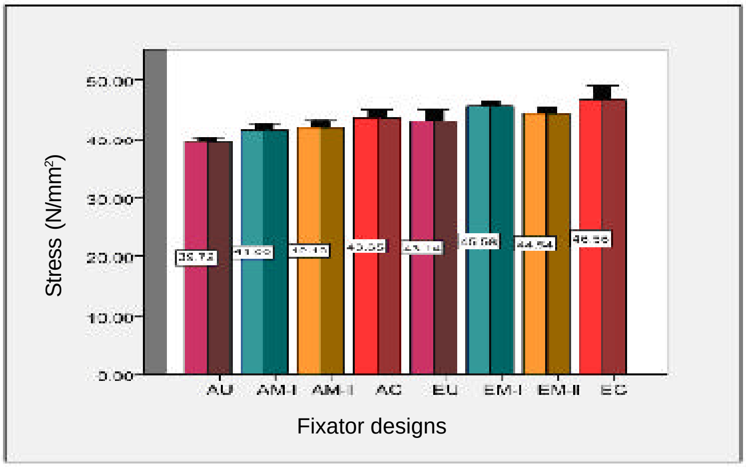


__Fig. 34:__ Mean ± SE values of stress in different designs of acrylic and epoxy fixators.

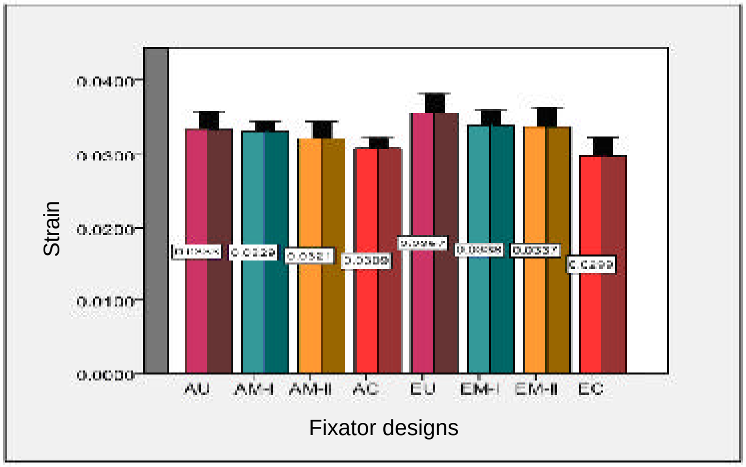


__Fig. 35:__ Mean ± SE values of strain in different designs of acrylic and epoxy fixators.

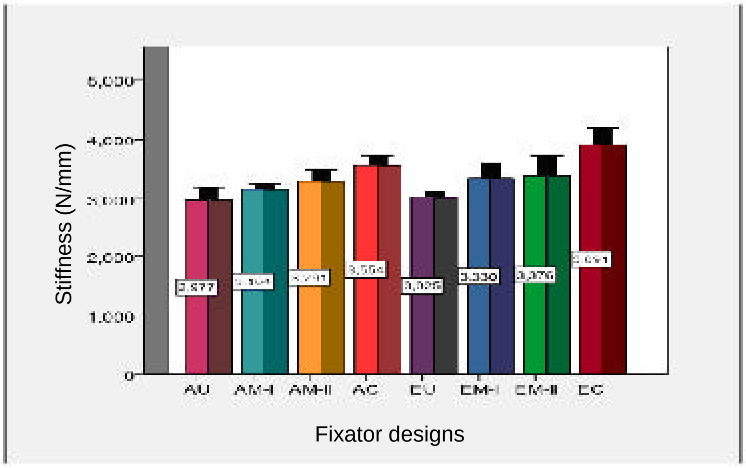


__Fig. 36:__ Mean ± SE values of stiffness in different designs of acrylic and epoxy fixators.

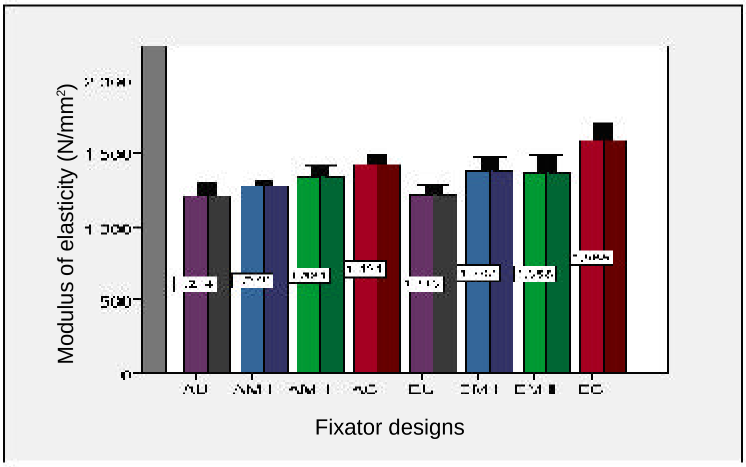


Fig. 37: *Mean ± SE values of modulus of elasticity in different designs of acrylic and epoxy fixators.*

Three-point fixation constructs

The average stress, stiffness and modulus of elasticity for fixator constructs with 12 pins (multiplanar/circular designs) were significantly (P<0.01) more than for 6 pin constructs (uniplanar design). Whereas, 6 pin constructs had significantly higher values of strain than 12 pin constructs (Figs. 38, 39, 40 and 41).

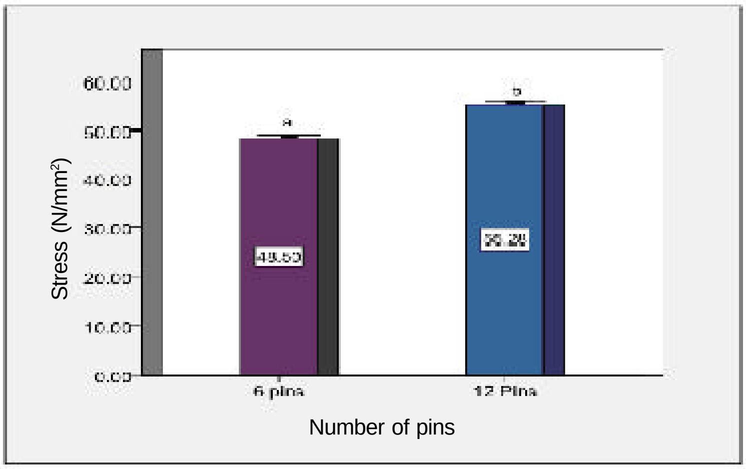


Fig. 38: *Mean ± SE values of stress in the fixators having 6 or 12 pins.*

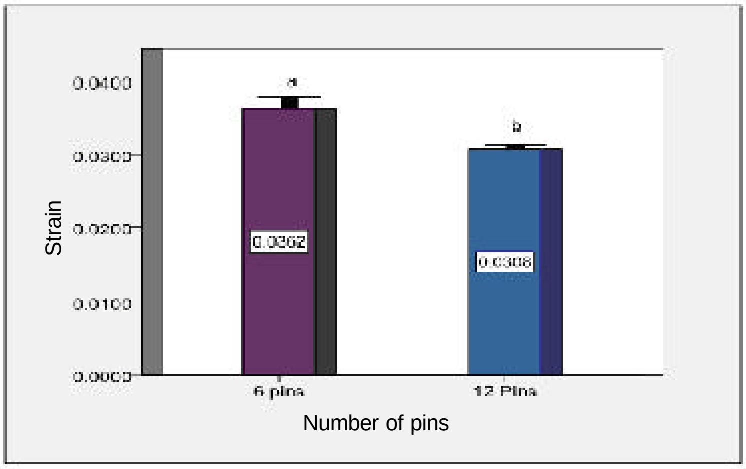


Fig. 39: *Mean ± SE values of strain in the fixators having 6 or 12 pins.*

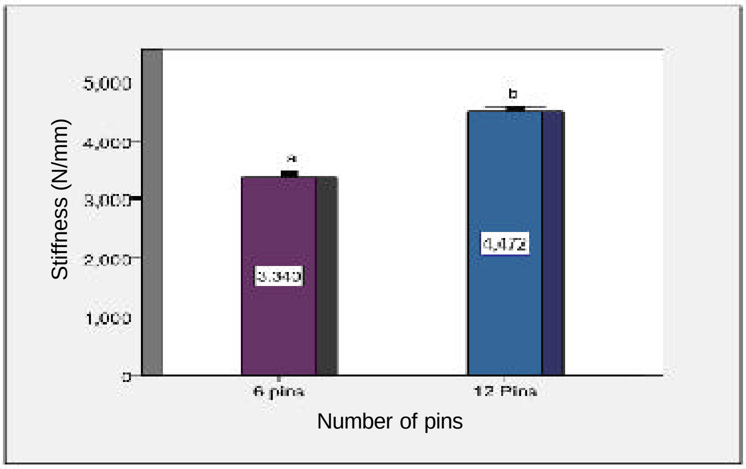


Fig. 40: *Mean ± SE values of stiffness in the fixators having 6 or 12 pins.*

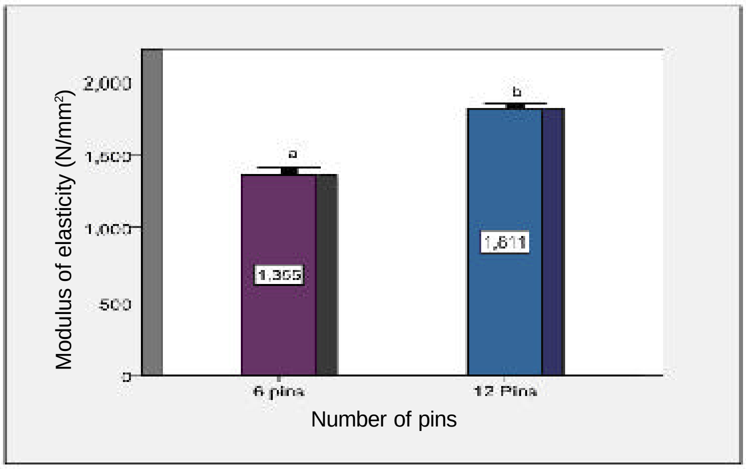


Fig. 41: *Mean ± SE values of modulus of elasticity in the fixators having 6 or 12 pins.*

No significant (P>0.05) difference was recorded in the values of stress, strain, stiffness and modulus of elasticity between the acrylic and epoxy fixators (Figs. 42, 43, 44 and 45).

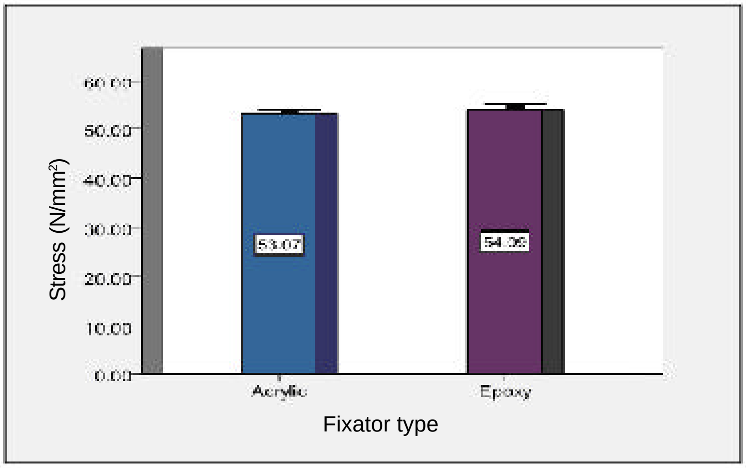


Fig. 42: *Mean ± SE values of stress in acrylic and epoxy fixators.*

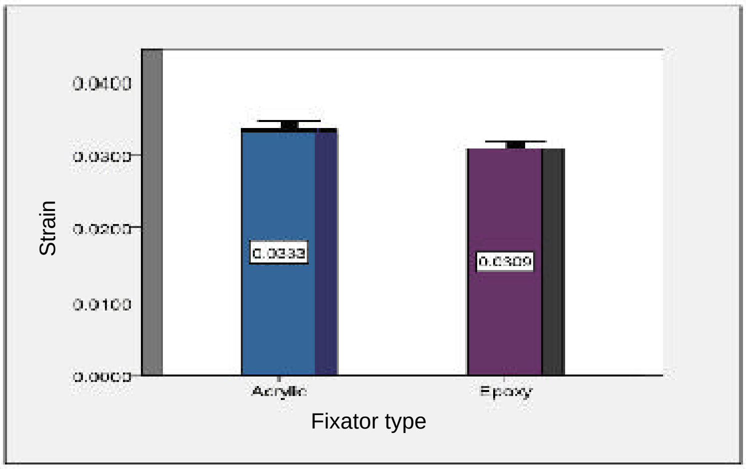


Fig. 43: *Mean ± SE values of strain in acrylic and epoxy fixators.*

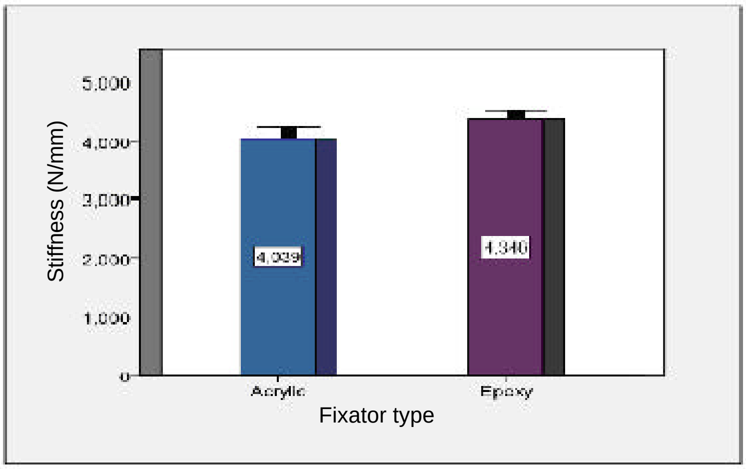


Fig. 44: *Mean ± SE values of stiffness in acrylic and epoxy fixators.*

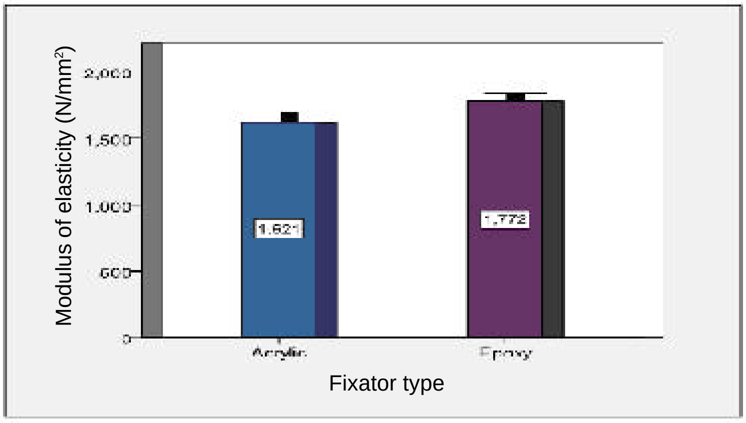


Fig.45: *Mean ± SE values of modulus of elasticity in acrylic and epoxy fixators.*

A significant ($P<0.01$) difference in mean ± SE value of stress was recorded with circular design having the highest value, followed by multiplanar-II and I designs, and uniplanar design which had the lowest value (Fig. 46).

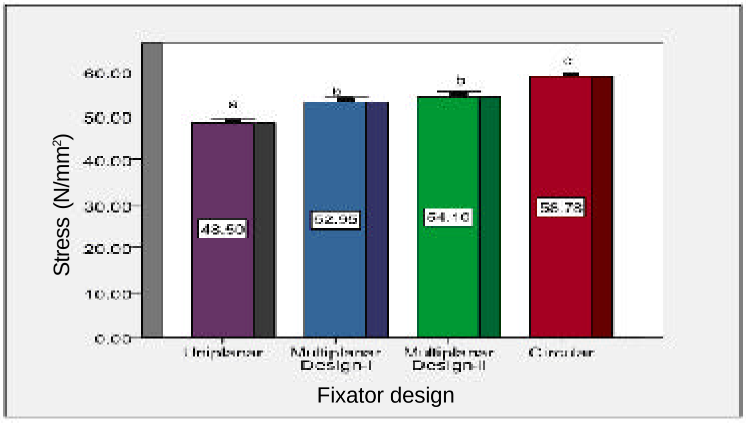


Fig. 46: *Mean ± SE values of stress in different designs of fixators.*

Among the different designs, a significantly ($P<0.05$) higher value of strain was recorded in uniplanar design than the other three (Fig. 47).

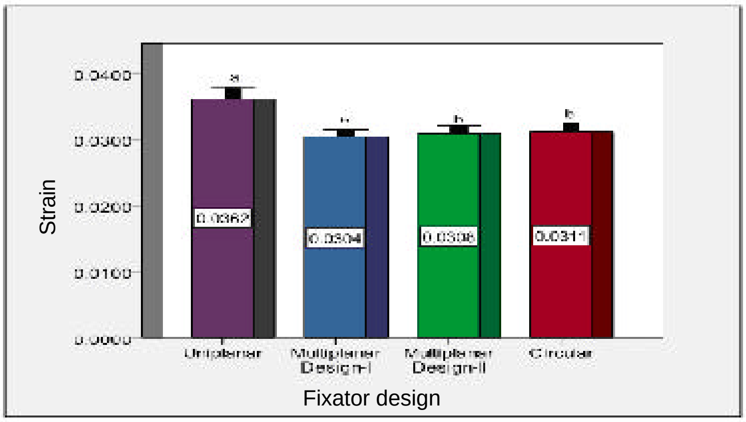


Fig. 47: *Mean ± SE values of strain in different designs of fixators.*

There was a non significant (P>0.05) difference in the stiffness and modulus of elasticity between circular and multiplanar-I and II designs; whereas the values for uniplanar design were significantly (P<0.01) lower than the other 3 designs (Figs. 48 and 49).

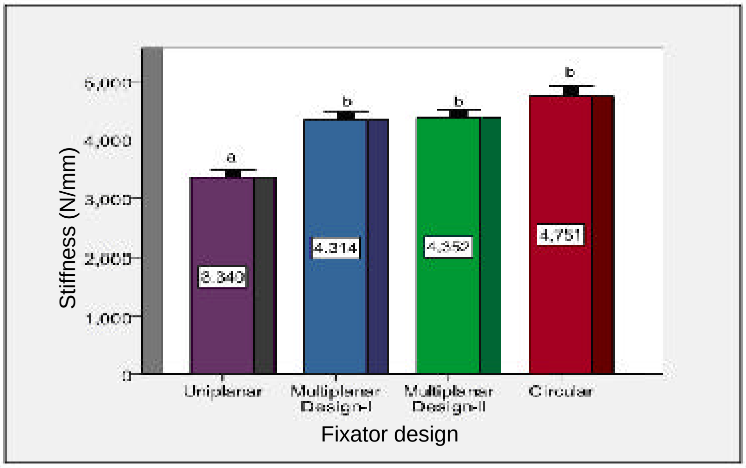


Fig. 48: *Mean ± SE values of stiffness in different designs of fixators.*

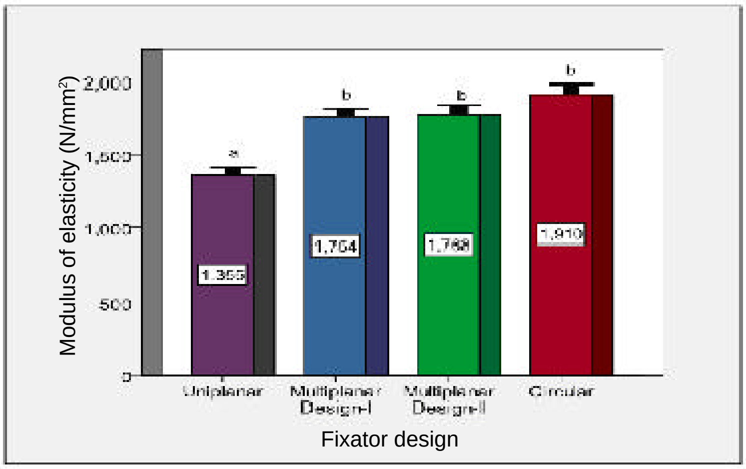


Fig. 49: *Mean ± SE values of modulus of elasticity in different designs of fixators.*

The mean ± SE value of stress for epoxy circular fixator was non significantly (P>0.05) higher than for acrylic circular fixator, however, it was significantly (P<0.01) higher than the values for the other fixators. The acrylic circular design was non significantly (P>0.05) different from acrylic multiplanar-I and II and epoxy multiplanar-I and II designs. The mean ± SE value of stress for acrylic uniplanar design was the lowest (Fig. 50).

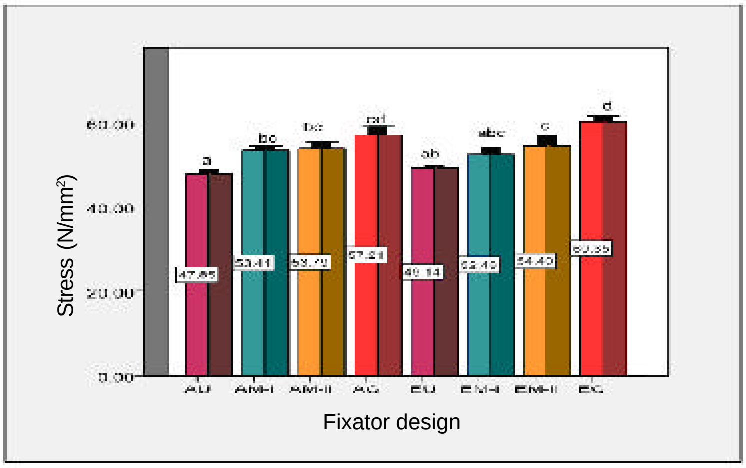


Fig. 50: *Mean ± SE values of stress in different designs of acrylic and epoxy fixators.*

Among the different designs of acrylic and epoxy fixators, relatively higher values of strain were recorded in acrylic and epoxy uniplanar designs. Further, in acrylic group the values of strain were non significantly (P>0.05) different among the 4 designs. Similarly, among the epoxy group the values of strain were non significantly (P>0.05) different among the 4 designs (Fig. 51).

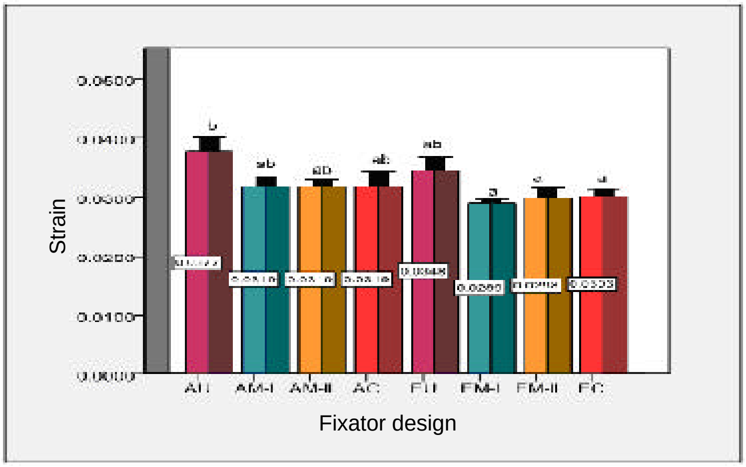


Fig. 51: *Mean ± SE values of strain in different designs of acrylic and epoxy fixators.*

The mean ± SE values of stiffness and modulus of elasticity for epoxy circular and acrylic circular designs were non significantly (P>0.05) higher than the multiplanar designs. There was no significant (P>0.05) difference between multiplanar designs of epoxy and acrylic fixators. The values of stiffness and modulus of elasticity for uniplanar designs of both epoxy or acrylic fixators were significantly (P<0.05) lower than all other designs (Figs. 52 and 53).

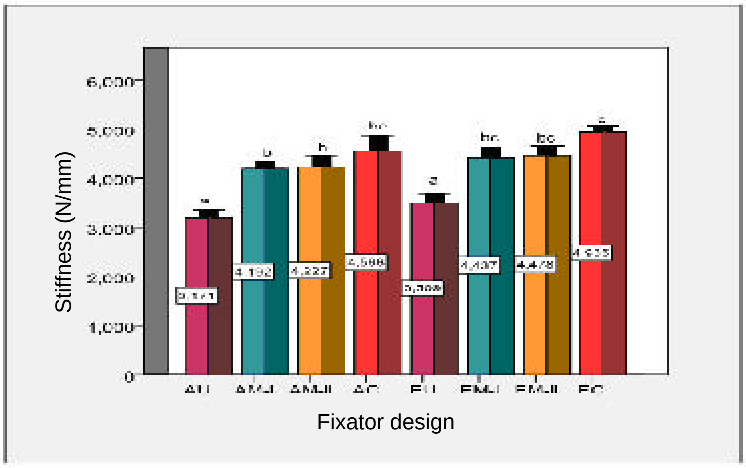


Fig. 52: *Mean ± SE values of stiffness in different designs of acrylic and epoxy fixators.*

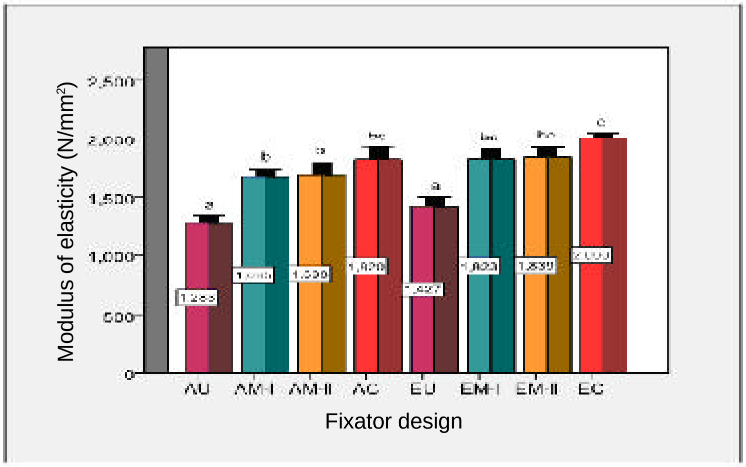


Fig. 53: *Mean ± SE values of modulus of elasticity in different designs of acrylic and epoxy fixators.*

Comparison between 2-point and 3-point fixation constructs

The mean ± SE values of stress (N/mm^2), strain, stiffness (N/mm) and modulus of elasticity (N/mm^2) for fixators having 2-point and 3-point fixation per segment of rods was recorded. Significantly ($P<0.01$) higher values of stress, stiffness and modulus of elasticity were recorded in the ESF constructs with 3-point fixation per segment than in 2-point fixation per segment. Strain followed the opposite trend with lower value in 3-point fixation constructs (Figs. 54, 55, 56 and 57).

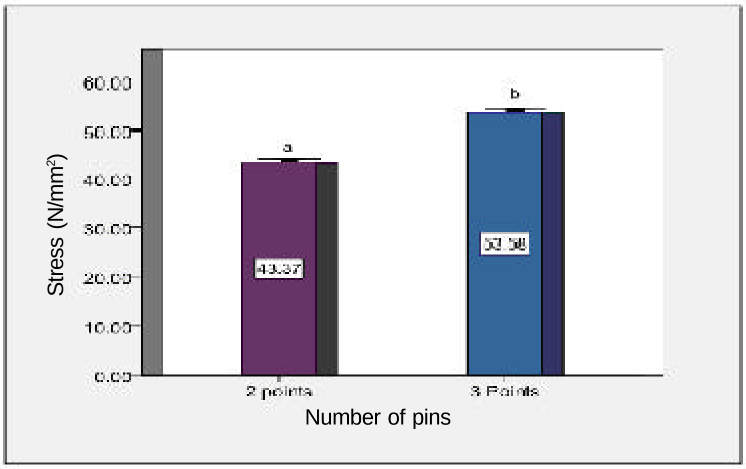


Fig. 54: *Mean ± SE values of stress in fixator constructs having 2- or 3- point support per segment.*

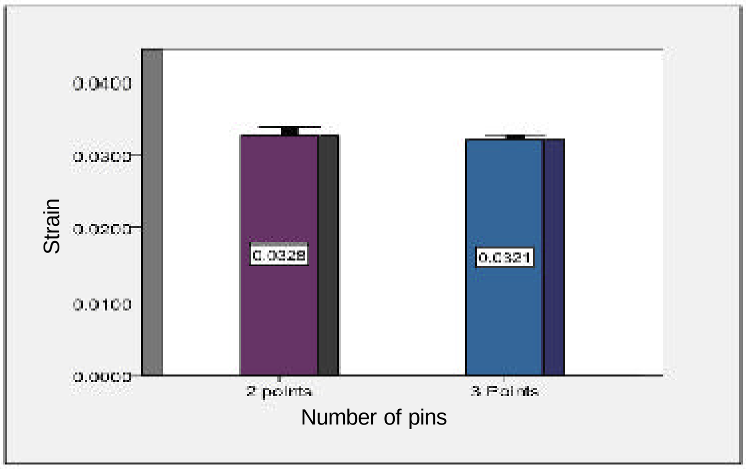


Fig. 55: *Mean ± SE values of strain in fixator constructs having 2- or 3- point support per segment.*

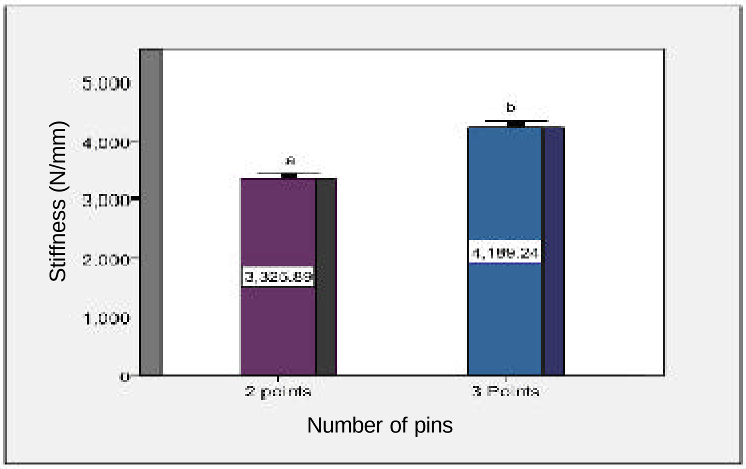


Fig. 56: *Mean ± SE values of stiffness in fixator constructs having 2- or 3- point support per segment.*

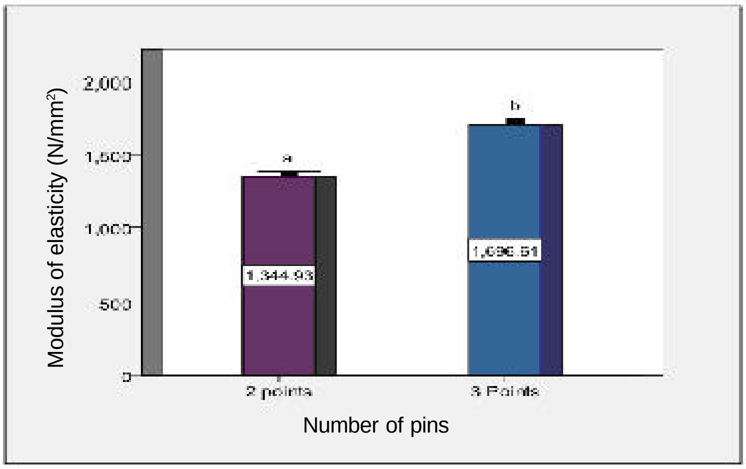


Fig. 57: *Mean ± SE values of modulus of elasticity in fixator constructs having 2- or 3-point support per segment.*

Bending

The values of bending moment, stiffness and modulus of elasticity for acrylic and epoxy fixators were comparable and there was no significant (P>0.05) difference between them (Figs. 58, 59 and 60).

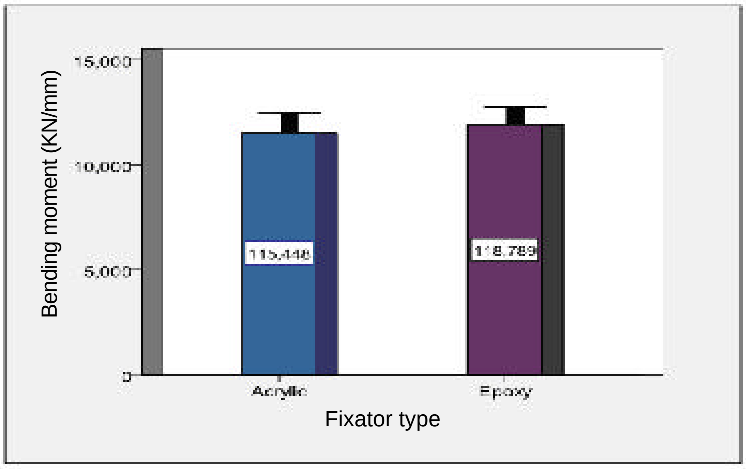


Fig. 58: *Mean ± SE values of bending moment for acrylic and epoxy fixators.*

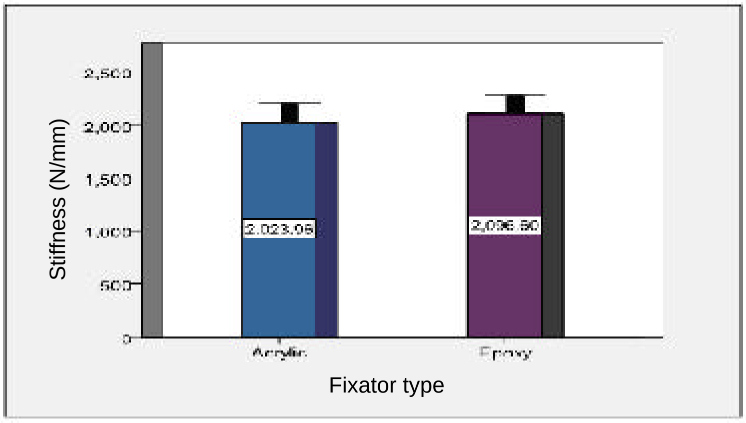


Fig. 59: *Mean ± SE values of stiffness for acrylic and epoxy fixators.*

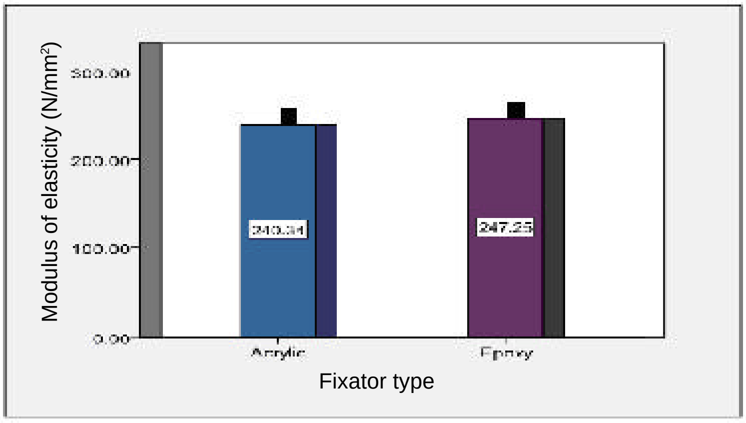


Fig. 60: *Mean ± SE values of shear modulus for acrylic and epoxy fixators.*

The mean ± SE values of bending moment, stiffness and modulus of elasticity for circular designs were significantly (P<0.01) higher than for multiplanar designs (I and II). Further, the values for multiplanar designs were significantly (P<0.01) higher than for uniplanar designs (Figs. 61, 62, 63).

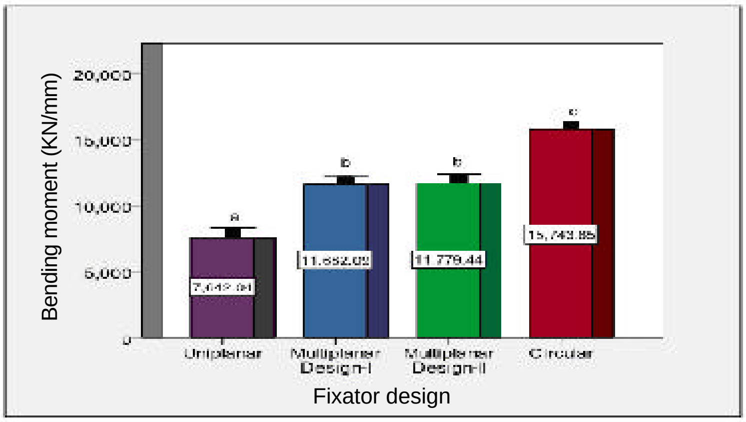


Fig. 61: *Mean ± SE values of bending moment for different designs of fixators.*

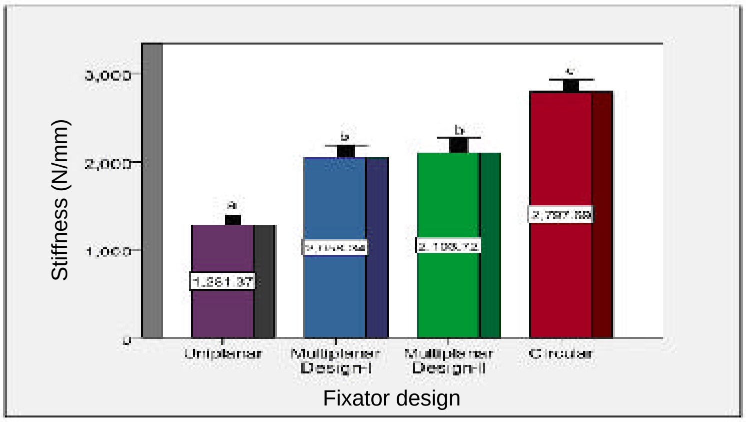


Fig. 62: *Mean ± SE values of stiffness for different designs of fixators.*

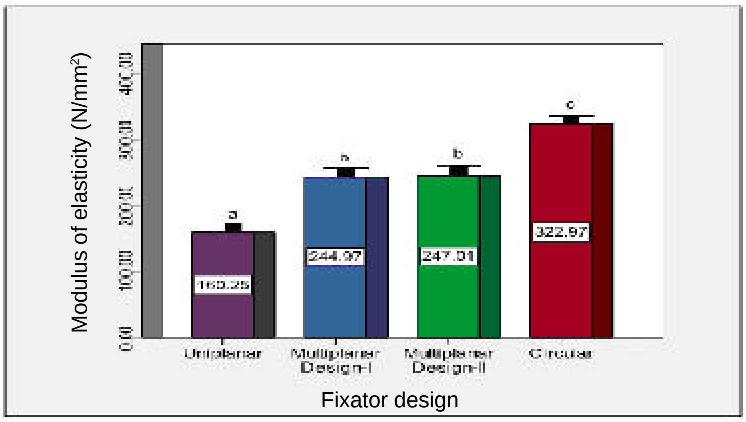


Fig. 63: *Mean ± SE values of shear modulus for different designs of fixators.*

The mean ± SE values of bending moment, stiffness and modulus of elasticity did not differ significantly between the acrylic and epoxy fixators with respect to corresponding designs (Figs. 64, 65, 66).

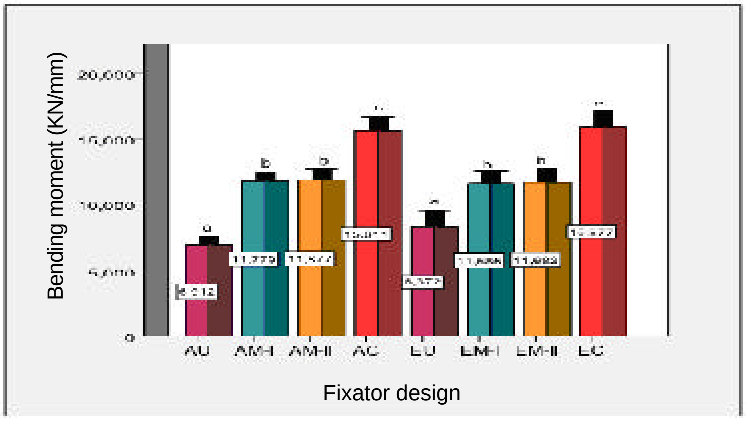


Fig. 64: *Mean ± SE values of bending moment for different designs of acrylic and epoxy fixators.*

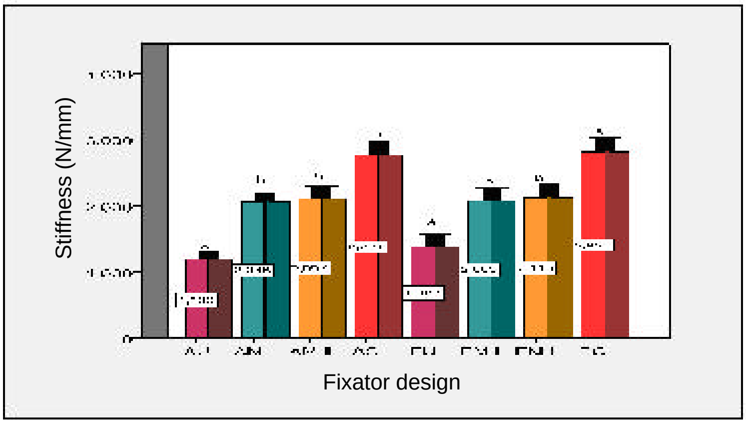


Fig. 65: Mean ± SE values of stiffness for different designs of acrylic and epoxy fixators.

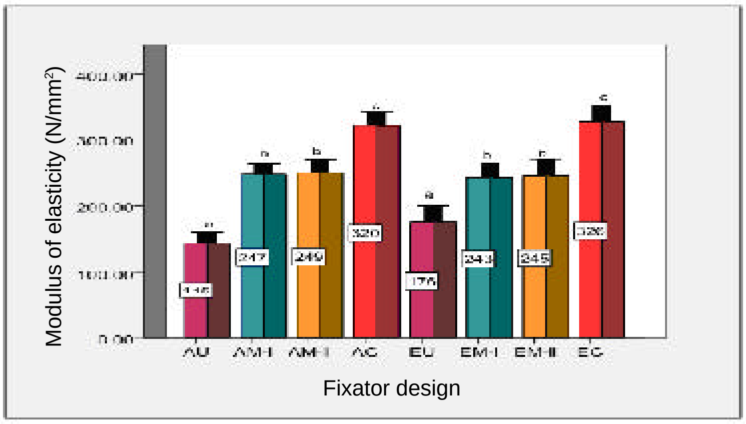


Fig. 66: Mean ± SE values of shear modulus for different designs of acrylic and epoxy fixators.

Torsion

The mean ± SE values of shear stress (N/mm^2), shear modulus (N/mm^2) and stiffness (Nm/deg) for epoxy fixator constructs were non significantly (P>0.05) higher than for acrylic fixator constructs (Figs. 67, 68 and 69).

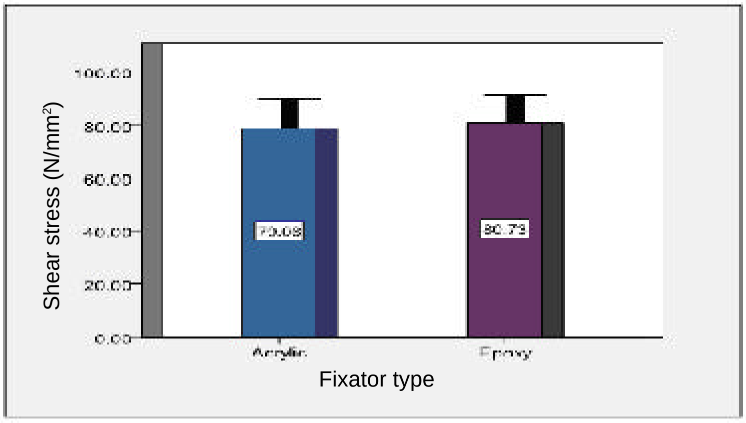


Fig. 67: Mean ± SE values of shear stress in acrylic and epoxy fixators.

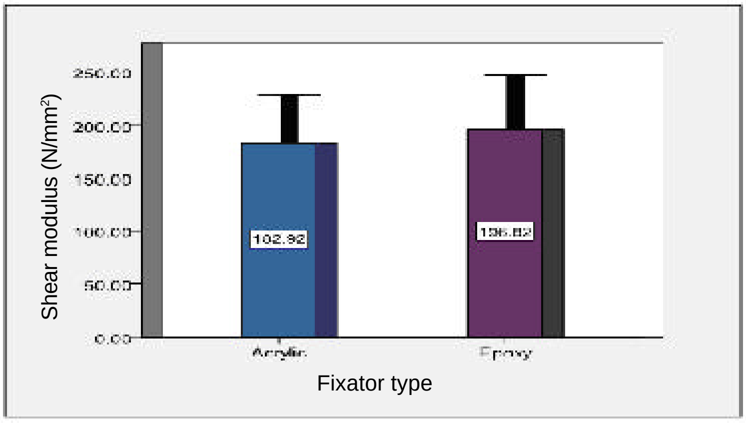


Fig. 68: *Mean ± SE values of shear modulus in acrylic and epoxy fixators.*

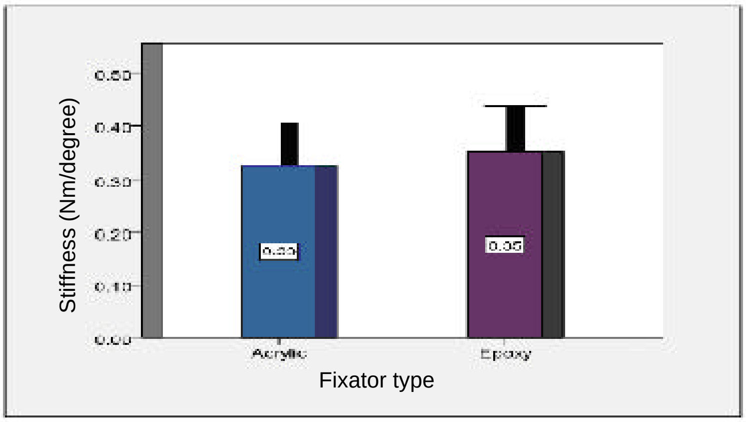


Fig. 69: *Mean ± SE values of stiffness in acrylic and epoxy fixators.*

The mean ± SE values of shear stress, shear modulus and stiffness were significantly (P<0.01) higher in circular design than others. Significant (P<0.05) difference was also recorded between multiplanar-I and multiplanar- II designs. The values for uniplanar design were significantly (P<0.01) lower than others (Figs. 70, 71 and 72).

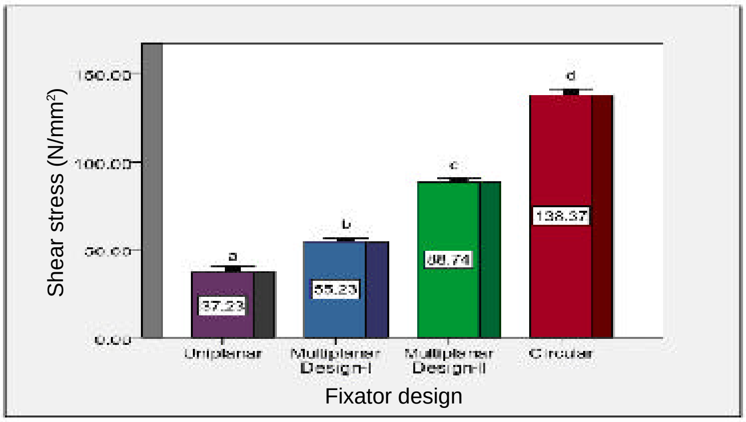


Fig.70: *Mean ± SE values of shear stress in different designs of fixators.*

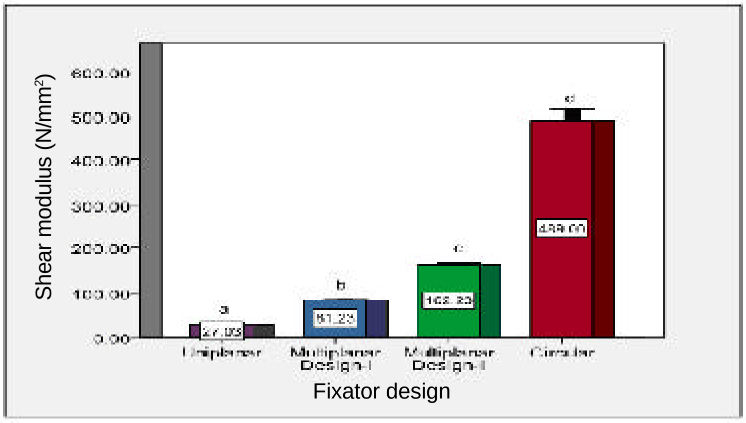


Fig. 71: *Mean ± SE values of shear modulus in different designs of fixators.*

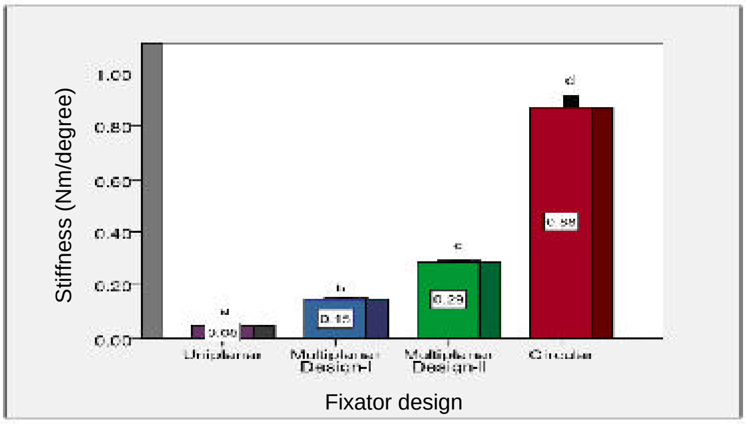


Fig. 72: *Mean ± SE values of stiffness in different designs of fixators.*

The mean ± SE values of shear stress differed significantly (P<0.01) between all the 4 designs, both in acrylic and epoxy fixators. The shear stress was the least in uniplanar design followed by multiplanar design-I, multiplanar design-II and circular designs (Fig. 73). No significant difference was seen between acrylic and epoxy fixators of a particular design.

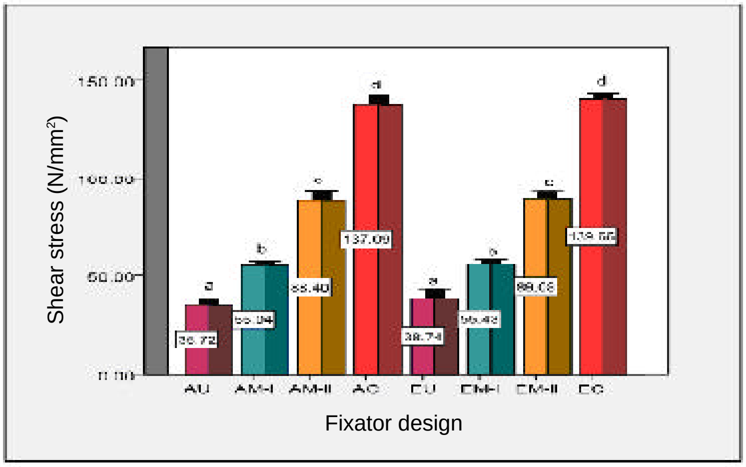


Fig.73: *Mean ± SE values of shear stress in different designs of acrylic and epoxy fixators.*

The values of shear modulus and stiffness were similar for acrylic uniplanar and epoxy uniplanar designs, acrylic multiplanar-I and epoxy multiplanar-I designs, whose values were significantly (P<0.01) lower than for respective acrylic and epoxy multiplanar-II designs. A significantly (P<0.01) higher value was recorded for epoxy and acrylic circular designs than other designs. Further, epoxy circular design recorded the highest values, which were significantly more (P<0.01) than acrylic circular design (Figs. 74 and 75).

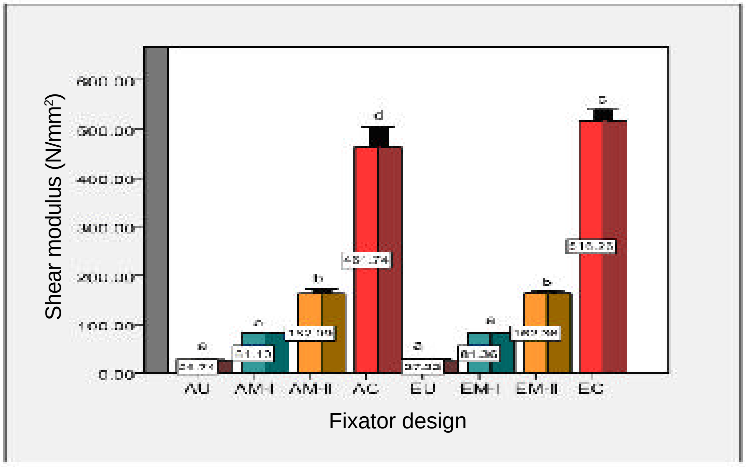


***Fig. 74:** Mean ± SE values of shear modulus in different designs of acrylic and epoxy fixators.*

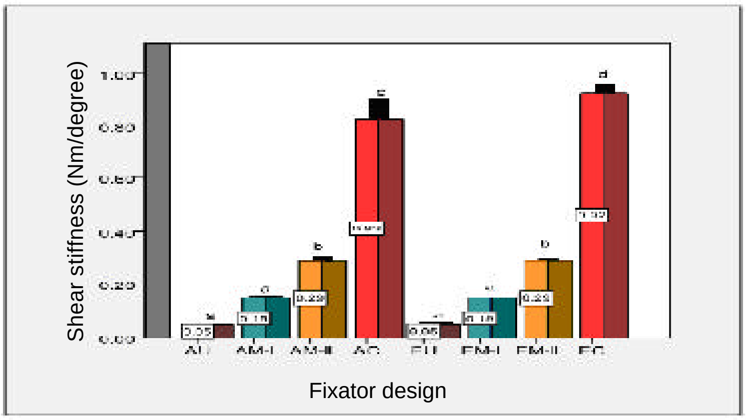


***Fig. 75:** Mean ± SE values of stiffness in different designs of acrylic and epoxy fixators.*

The values of shear modulus and stiffness between multiplanar design-I and multiplanar design-II differed significantly (in both acrylic and epoxy fixators), with design-II showing the values nearly double than that of design-I.

Part 3: Clinical evaluation of acrylic and epoxy-pin external skeletal fixation systems in fracture treatment

Preoperative observations

Based on the history and clinical examination, different observations were recorded (Table 5). A total of 24 dogs were treated with 27 fractures. Among them, 3 dogs were having bilateral R/U fractures.

Relatively more number of R/U (n=17) fractures were recorded, whereas, 10 cases were of T/F fractures (Fig. 76). Out of 17 R/U cases presented, 10 fractures were located at the distal third of diaphysis, 5 were epiphyseal and 2 were diaphyseal fractures. Among tibial fracture cases, 5 cases were diaphyseal fracture (1 proximal third, 4 distal third and 3 mid diaphyseal) and one each of epiphyseal fracture and joint luxation.

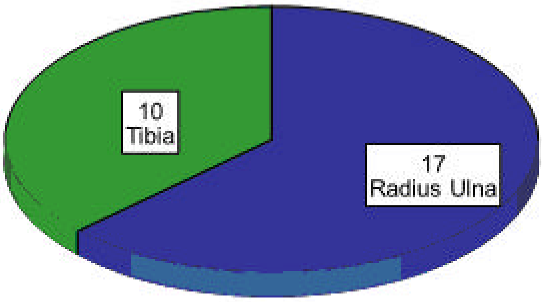


Fig. 76: Number of cases with radius / ulna or tibial fractures.

Twenty cases were treated with closed (simple) fractures and seven cases were having open (compound) fractures (Fig. 77). Eighteen dogs were males and 9 were females (Fig. 78).

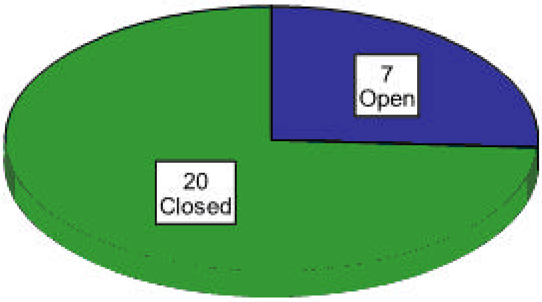


Fig. 77: Number of open and closed fractures treated.

Table 5 : *Clinical parameters of animals treated with acrylic / epoxy ESF.*

Case No.	Treatment group	Breed	Age	Sex	Weight (kg)	Cause of injury	Time since fracture (days)	Open/ closed	Degree of soft tissue trauma	Type & location of fracture/luxation
1	Group I (Acrylic-Radus /Ulna)	Rottweiller	9 m	F	14	Fall	20	Closed	Slight	Rt Distal epiphyseal fracture (Salter Harris Type-II)
2		Labrador	1.5 y	M	30	Fall	5	Closed	Slight	Lt Distal epiphyseal fracture (Salter Harris Type-II)
3		German shepherd	4 y	M	25	RTA	11	Open	Moderate	Lt Transverse distal 3rd diaphyseal fracture
4		Mongrel	3m	M	7	Fall	2	Closed	Slight	Rt Slight oblique middiaphyseal fracture
5		Spitz	6 y	M	13	Fall	5	Closed	Slight	Lt Transverse distal 3rd diaphyseal fracture
6		Mongrel	2 y	M	14	Hit by stick	15	Closed	Slight	Lt Slight oblique distal 3rd diaphyseal fracture
7		Spitz	8 m	F	5	Fall	2	Open	Moderate	Rt Distal epiphyseal comminuted fracture (Salter Harris Type-II)
8	Group II (Acrylic-Tibia/Fibula)	Mongrel	9 m	F	12	Fall	17	Closed	Slight	Lt Transverse middiaphyseal fracture T/F
9		Mongrel	6 m	M	10	Fall	6	Closed	Slight	Rt Slight oblique prox 3rd diaphyseal comminuted fracture
10		Great Dane	1 y	M	35	RTA	5	Open	Slight	Lt Slight oblique middiaphyseal fracture
11		Mongrel	1 y	M	16	RTA	7	Closed	Slight	Lt Distal 3rd diaphyseal transverse fracture
12		Mongrel	11 m	F	15	RTA	10	Closed	Slight	Lt Slight oblique distal 3rd diaphyseal fracture

Table 5 : *Clinical parameters of animals treated with acrylic / epoxy ESF (Contd...).*

Case No.	Treatment group	Breed	Age	Sex	Weight (kg)	Cause of injury	Time since fracture (days)	Open/ closed	Degree of soft tissue trauma	Type & location of fracture/luxation
13	Group III (Epoxy Radius/ Ulna)	Mongrel	4 m	M	10	Hit by stick	4	Closed	Slight	Rt Distal 3rd transverse diaphyseal fracture
14		Labrador	1 y	M	24	RTA	1	Open	Slight	Rt Distal 3rd communited diaphyseal fracture
15		Rottweiler	9 m	F	14	Fall	20	Close	Slight	Lt Epiphyseal fracture (Salter Harris Type II)
16		Labrador	9m	F	22	RTA	30	Closed	Slight	Lt Transverse distal 3rd communited diaphyseal fracture
17		Labrador	1.5 y	M	30	Fall	5	Closed	Slight	Rt Slight oblique distal 3rd diaphyseal fracture
18		German shepherd	5 y	M	47	RTA	5	Closed	Severe	Rt Distal 3rd diaphyseal fracture of R/U and meta carpals 2,3 and 4
19		Mongrel	4m	M	10	Fall	20	Closed	Slight	Lt. Distal 3rd diaphyseal fracture
20		Mongrel	11 yr	M	15	Fall	2	Closed	Slight	Rt Transverse middiaphyseal fracture
21		Mongrel	2 y	M	14	Hit by stick	15	Closed	Slight	Rt Slight oblique distal 3rd diaphyseal fracture
22		Spitz	8 m	F	5	Fall	2	Open	Moderate	Lt Distal epiphyseal comminuted fracture (Salter Harris Type-II)
23	Group IV (Epoxy Tibia/Fibula)	Mongrel	4 y	F	12	Fall	30	Closed	Severe	Rt Middiaphyseal transverse fracture
24		Spitz	5 y	F	12	Hit by stick	6	Closed	Slight	Rt Communited slight oblique distal third diaphyseal fracture
25		Mongrel	2 y	M	13	RTA	2	Closed	Moderate	Lt. proximal epiphyseal fracture
26		Doberman	8 m	M	15	RTA	4	Open	Severe	Lt Distal 3rd communited diaphyseal fracture
27		Spitz	1.5 y	M	14	RTA	7	Open	Slight	Dislocation of left tibio-tarsal joint

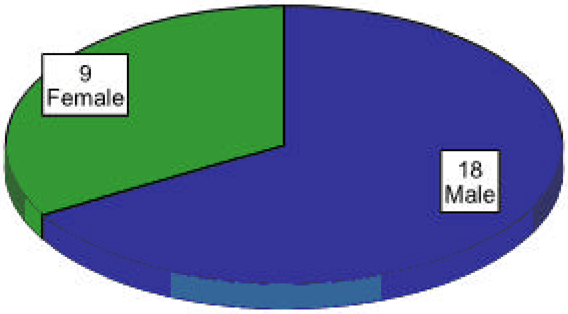


Fig. 78: *Number of male and female dogs treated.*

Among different breeds presented, 12 dogs were mongrels. Labrador (4), Spitz (4), German shepherd (3), Rottweiler (2), Great Dane (1) and Doberman (1) were the other breeds presented with long bone fractures (Fig. 79).

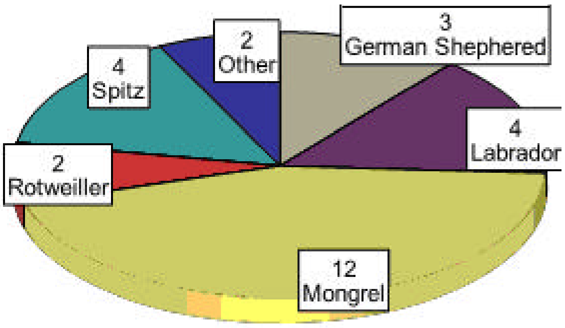


Fig. 79: *Different breeds of dogs presented with fractures.*

Of the dogs treated, 6 dogs had body weight up to 10 kg, 13 dogs were weighing 10-20 kg and 8 dogs were having weight more than 20 kg (Fig. 80).

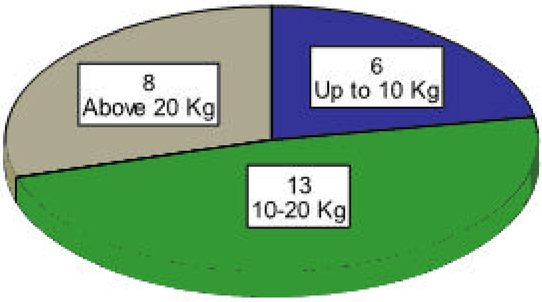


Fig. 80: *Number of animals treated in different weight groups.*

Fall from height was the most common cause (13 cases) of fracture, followed by road traffic accident (11 cases) and hit by stick (3 cases) (Fig. 81).

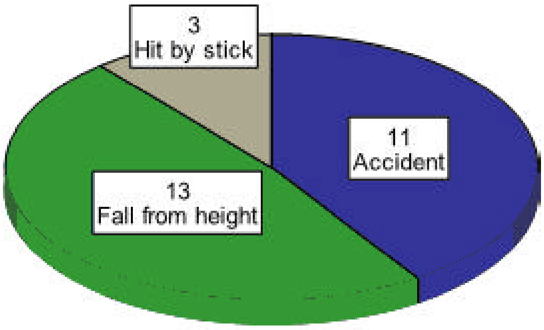


Fig. 81: *Number of animals presented with different causes of fracture.*

Fourteen cases were presented to the clinic within 5 days of injury, 7 cases were presented between 5 and 15 days, and 6 animals were presented after 15 days of fracture/ injury (Fig. 82).

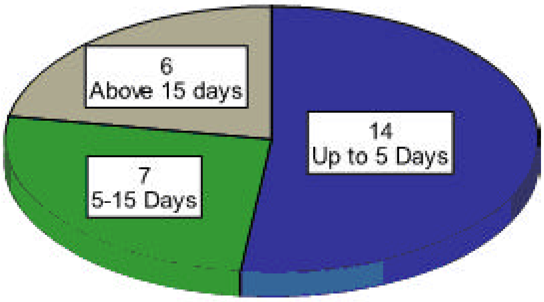


Fig. 82: *Number of animals presented at different time since injury.*

Degree of trauma was slight in 20 cases, moderate in 4 cases and 3 cases had severe soft tissue trauma (Fig. 83).

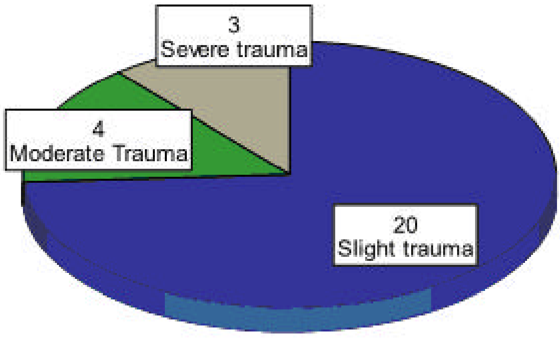


Fig. 83: *Number of animals presented with different degrees of trauma.*

Intraoperative observations

The number and size of pins used (cross and single) has been given in table 6. The most common pin diameter used was 1.5 mm in T/F and R/U. The angle between the pins

Table 6: *Intraoperative observations in animals of different groups.*

S.No	Treatment group	No. of cross (pair) pins	No. of single pins	Total pins	Diameter of pin (in mm)	Time for fracture redcution (mm)	Time (min) for passing wires (A)	Time (min) for applying fixator (B)	Time (min) for hardening (C)	Total time (min) (A+B+C)
1	Group I (Acrylic-Radius/Ulna)	2	3	7	1.5	-	15	20	10	70
2		3	3	9	1.5	-	15	30	12	82
3		4		10	1.5	-	10	20	11	41
4		4		8	1.5	-	20	30	10	60
5		4		8	1.5	-	15	30	8	53
6		4		8	1.5	30	10	20	11	41
7		3	3	9	1.5 /1.25	5	10	40	13	63
8	Group II (Acrylic-Tibia/Fibula)	4		8	1.5	-	16	35	10	61
9		4		8	1.25	10	20	20	12	52
10		4		8	1.5	22	16	35	12	61
11		4		8	1.5	-	17	40	10	67
12		4		8	1.5	-	15	35	9	59
13	Group III (Epoxy-Radius/Ulna)	3	2	8	1.5	-	15	15	20	50
14		4		8	1.5	17	15	30	20	65
15		2		7	1.5	15	12	15	22	59
16		4		8	1.5	-	15	15	21	51
17		3	3	9	1.5	-	15	20	20	55
18		4	3	11	1.5	-	18	20	23	61
19		4	3	11	1.5	20	10	10	22	42
20		4		8	1.5	5	8	20	23	51
21		4		8	1.5	20	20	30	25	75
22		3	3	9	1.5/1.25	15	10	20	27	57
23	Group IV (Epoxy-Tibia/Fibula)	4		8	1.5	30	15	15	20	50
24		4		8	1.5	15	15	20	21	46
25		2	3	7	1.5	26	25	20	23	68
26		4		8	1.5	20	20	20	21	61
27		3	3	9	1.5	-	15	25	22	62

varied from 50°-80°, based on the type and location of fracture. The pins (1.2-1.5 mm) could be inserted through the metacarpal and metatarsal bones, mediolaterally, with ease. No iatrogenic fracture occurred.

In cases of epoxy fixation, pins in the same plane were bent and joined together, however, even when pins were in different planes, they were easily bent and joined, giving varied shape to the connecting bars. Additional pin pieces were sometimes used to make the scaffold. Joining the bent wires provided temporary stability until the epoxy-pin fixator construct fully hardened.

Unlike epoxy fixators, in acrylic fixators, bent pins could not be incorporated within the side bars (due to technical difficulties). The fixation pins were pierced through and through the PVC pipes used for construction of side bars. The extra length of pins coming out of side bars were cut and bent.

In general keeping the bone fragments in alignment and construction of side bars was relatively more difficult during acrylic fixation than epoxy fixation. A gap of about 1-2 cm was kept in between the skin and side bars, both in acrylic and epoxy fixation systems.

The time required for passing the pins, construction of side bars, hardening of acrylic/ epoxy and total time for fixator application have been given in table 6. The mean ± SE time required for passing the pins in case of acrylic and epoxy groups was 14.92 ± 1.00 min and 15.20 ± 1.13 min, respectively, with no significant (P>0.05) difference between acrylic and epoxy fixation (Fig. 84).

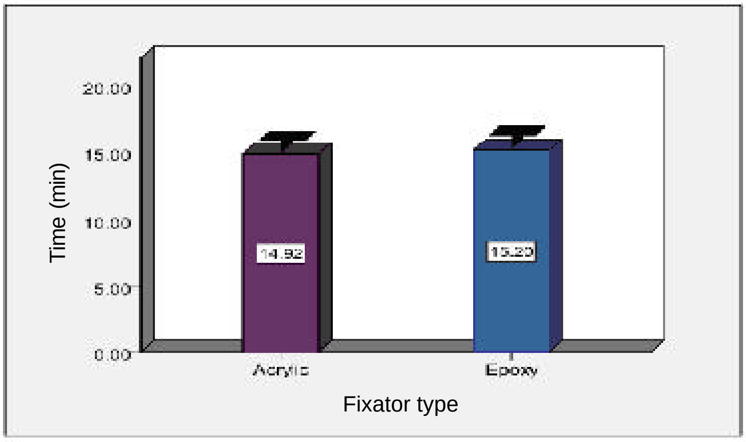


Fig. 84: *Mean ± SE time (min) required for passing the pins (construction of side bars).*

Time required for application of fixator (construction of side bars) in epoxy group was 19.67 ± 1.42 min, which was significantly ($P<0.05$) lesser than in acrylic group, where it was 29.58 ± 2.26 min (Fig. 85).

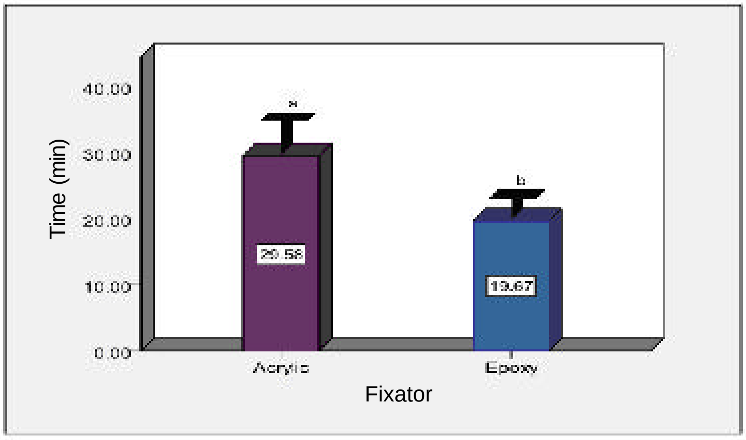


Fig. 85: *Mean ± SE time (min) required for application of fixator (construction of side bars).*

A significantly ($P<0.05$) more time for hardening/setting (22.00 ± 0.52 min) was recorded for epoxy fixators as compared to 10.67 ± 0.41 min for acrylic fixator (Fig. 86).

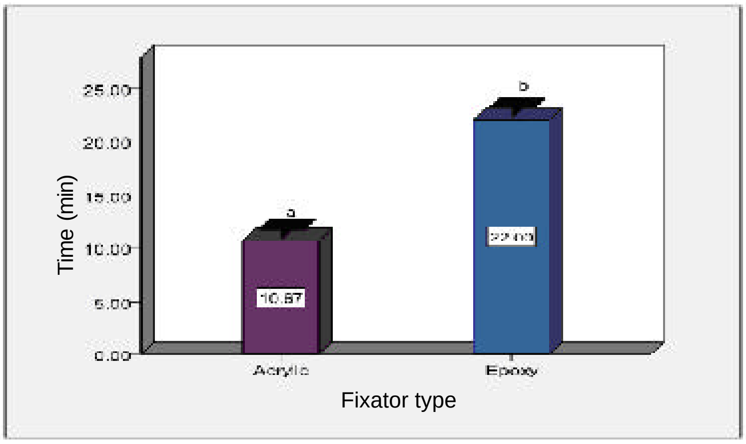


Fig. 86: *Mean ± SE time (min) required for hardening of acrylic or epoxy.*

However, the total time required for fixator application (passing pins, construction of side bars and hardening of acrylic/epoxy) did not differ significantly between the groups (Fig. 87).

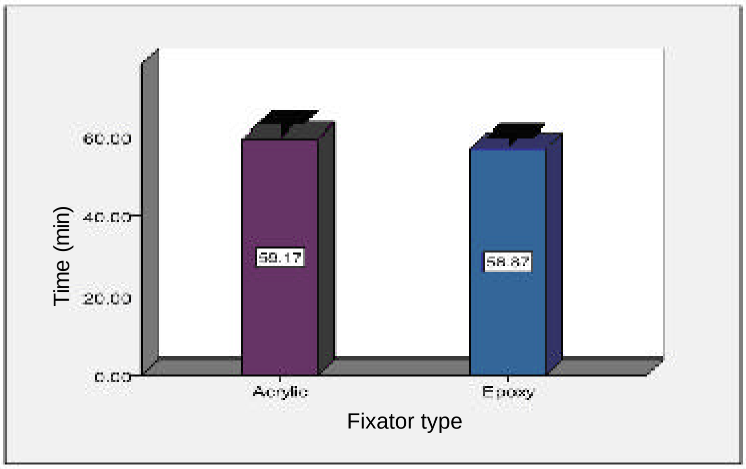


Fig. 87: *Mean ± SE total time (min required for fixator application.*

Complications

During the construction of acrylic fixators, fixation of pipe through the pins and construction of side bars was difficult. During mixing of acrylic powder with liquid, noxious and irritating fumes were produced. The handling was comparatively difficult due to liquid consistency of acrylic. Care had to be taken while pouring acrylic into the pipes which sometimes led to leakage from the pin-pipe interface. The setting/hardening time of acrylic was very less (11 min.), with limited scope for any adjustments. In addition, while setting/hardening of acrylic, a lot of heat was generated making it difficult to handle. Due to the ice kept in between the acrylic frame and skin (for cooling), the field became wet and dirty. No such complications were observed with epoxy fixation, and handling was easy due to its doughy consistency. No fumes were produced. There was negligible heat production during setting. Contouring and shaping the fixator frames according to the limbs was comparatively easier with epoxy putty. Further, due to slow setting of epoxy, minor adjustments in the frame and alignment of bone fragments were possible even during the frame construction.

Postoperative observations

The postoperative observations have been summarized in table 7.

Wound healing: A total of seven animals were treated with open fracture. In all the animals wound healed within 10 and 15 days.

Status of the fixation device: The fixation pins and side bars maintained their structures well in all the cases, barring two where the side bars were seen broken due to auto mutilation

Table 7: *Postoperative observations in animals of different groups.*

Case No.	Treatment groups	Level of fixation (days)	Time for healing	Postoperative complications (days)	Functional recovery
1	Group I	VG	30	_	VG
2	(Acrylic Radius / Ulna)	VG	55	Filling defect, loosening of most distal pin (3), moderate transudation from many pin tract	VG
3		S	45	_	G
4		G	30	_	VG
5		VG	45	Toe dragging (up to day 6)	VG
6		G	60	Loosening with slight transudation from one proximal pin tract (30)	VG
7		G	58	Moderate transudation, proximal & distal pair of pin tract (30)	VG
8	Group II	VG	35	Slight transudation of one proximal pin tract (3)	VG
9	(Acrylic Tibia/ Fibula)	VG	28	_	VG
10		G	65	Side bar broken due to auto mutilation (15)	G
11		S	60	_	G
12		G	45	_	VG
13	Group III	G	30	_	VG
14	(Epoxy Radius/Ulna)	G	45	Moderate transudation, first pin tract (3), distal pin broken (45)	VG
15		VG	30	Slight transudation, first pin tract (30)	VG
16		G	45	Moderate transudation, proximal & distal (30,45)	VG
17		S	55	Moderate transudation, first pin tract	G
18		S	60	(3) 2 pins break (15), Bar broken, reapplied	S
19		VG	60	_	VG
20		G	70	Osteolysis and slight transudation, most distal pair (45)	S
21		G	60	Slight transudation, proximal and distal pin tracts (7)	VG
22		G	58	_	VG
23	Group IV (Epoxy Tibia/Fibula)	G	60	On day 15-side bar broken, auto mutilated, fixator reapplied	G
24		S	60	Slight transudation, proximal pair of pin tracts (7)	G
25		VG	60	_	VG
26		G	35	_	G
27		G	50	_	G

VG = Very good; G = Good; S = Satisfactory (chewing by dogs) in one animal each with acrylic and epoxy fixator at 15th day post fixation. In the animal with epoxy fixator, epoxy was reapplied along the side bar construct. There was no breakage, bending or loosening of the pins in the fixators, except in two cases. Loosening of pins occurred in two animals with acrylic fixator in R/U. In the first case loosening of one pin occurred due to filling defect in the side bars. In another case loosening of one pin was reported at 45th day due to breakage of pin, the fixator was removed on the same day as fracture healing was evident radiographically.

Pin tract sepsis: No pin tract sepsis was observed in 16 cases. In 11 cases transudation from pin-skin interfaces was observed at various intervals. Slight exudation was seen in 6 animals, whereas in 5 animals moderate transudation was recorded. Transudation was mostly observed in most proximal and distal pins.

Gait analysis : The animals were observed for weight bearing during standing, walking and running on days 3, 7, 15, 30 and 45. All the animals showed a variable degree of lameness in the immediate postoperative days. There was a gradual increase in weight bearing (gait scores) at subsequent intervals (Fig. 88A).

Gait scores at standing: The gait scores for standing during the follow-up period between 3 and 45 days for different groups with respect to the fixator types (Fig. 88), sex of the animals (Fig. 89), treatment groups (Fig. 90), weight groups (Fig. 91), causes of injury (Fig. 92), types

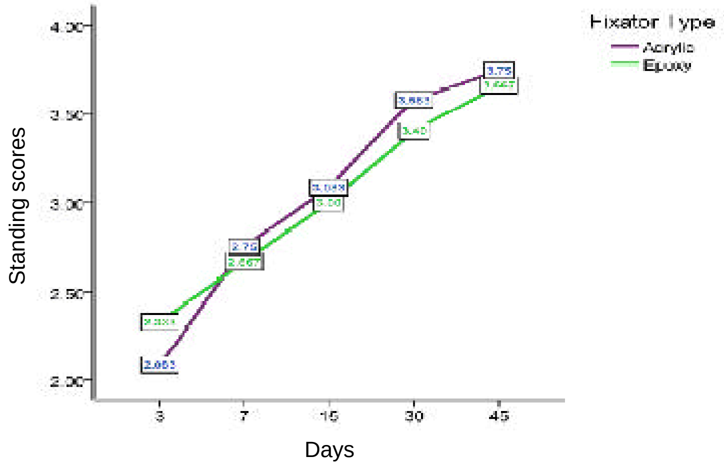


Fig. 88: *Mean ± SE values of standing scores in animals of acrylic and epoxy fixator groups on different days.*

Fig. 88A: *Dogs treated with acrylic / epoxy-pin ESF showing very good weight bearing during postoperative period.*

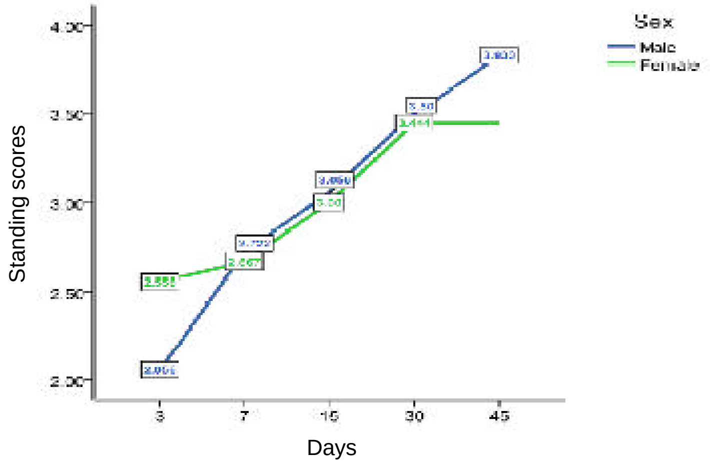


Fig. 89: *Mean ± SE values of standing scores in male and female animals on different days.*

of wound (Fig. 93), and bones involved (Fig. 94) were found to be non significantly (P>0.05) different.

Significant differences were observed among some of the gait scores during the follow-up period between different groups with respect to the age group, time since injury and degree of trauma, which are as follows:

Treated cases were analyzed according to their age after grouping them as 0-6 months, 6-12 months, 1-2 years and above 2 years (Fig. 95). The mean gait score in standing position on day 3 for animals above 2 years was significantly (P<0.05) lower than the mean scores for the animals in the age group of 6-12 months and 1-2 year; however, it was at par with the

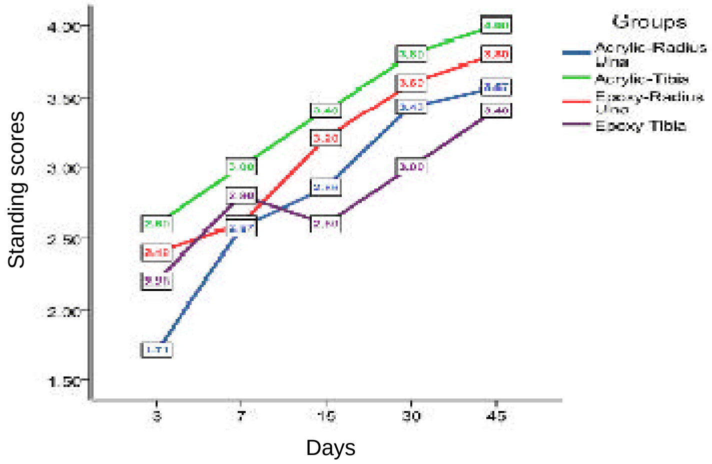


Fig. 90: *Mean ± SE values of standing scores in animals of different treatment groups on different days.*

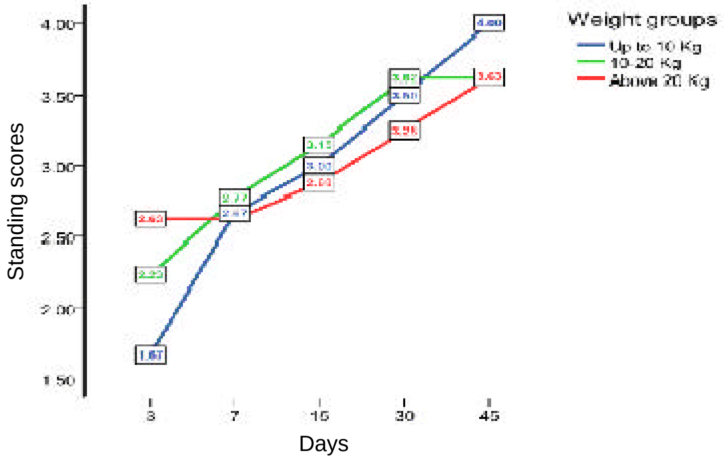


Fig. 91: *Mean ± SE values of standing scores in different weight groups on different days.*

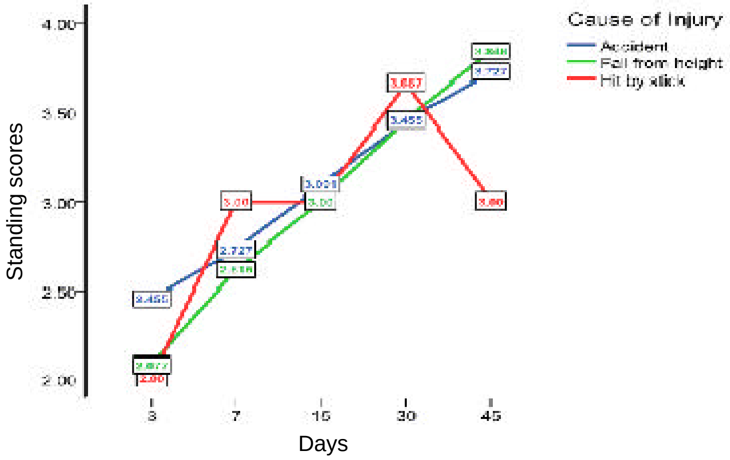


Fig. 92: *Mean ± SE values of standing scores in animals with different causes of injury on different days.*

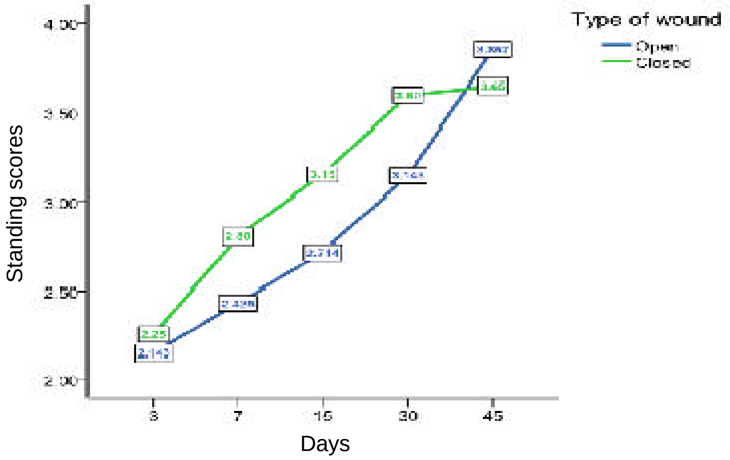


Fig. 93: *Mean ± SE values of standing scores in animals with open and closed fractures on different days.*

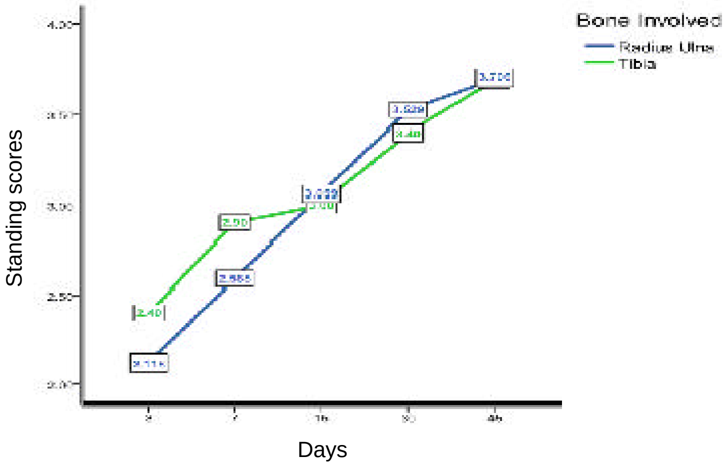


Fig. 94: *Mean ± SE values of standing scores in animals with fractures of R/U and tibia on different days.*

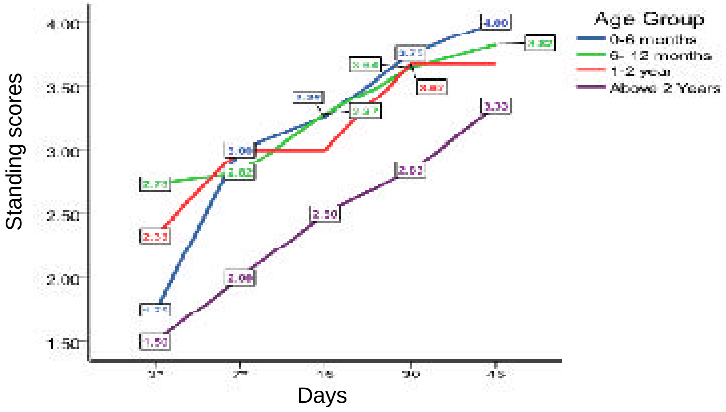


Fig.95: *Mean ± SE values of standing scores in animals of various age groups on different days*

scores of 0-6 month of age group animals. There was no significant (P>0.05) difference in the standing gait scores on days 7, 15, 30 and 45. The mean gait scores in standing position for 0-6 month animals on days 15, 30, and 45 were found to be the highest, however, the differences were non significant (P>0.05).

The gait was also analyzed with respect to the time since injury after grouping the animals on up to 5 days, 5-15 days and above 15 days (Fig. 96). The mean gait score in standing position on day 45 for animals presented within 5 days of injury was significantly (P<0.05) higher than those presented later. However, there was no significant (P>0.05) difference in the mean gait scores in standing position on days 3, 7, 15 and 30.

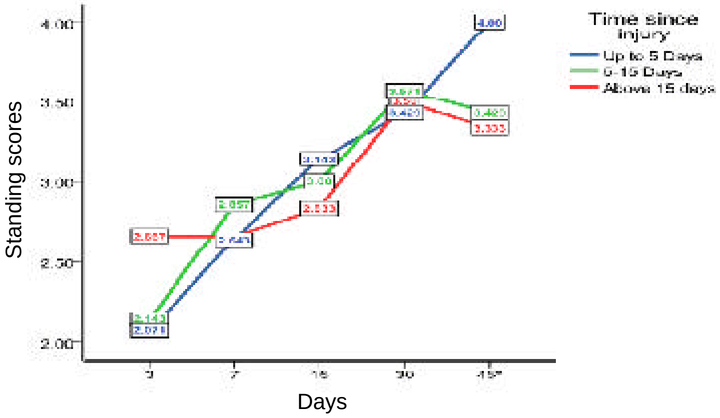


Fig. 96: *Mean ± SE values of standing scores in animals brought for treatment on different days of injury.*

Analysis of cases according to the degree of trauma was done by grouping them as slight, moderate and severe (Fig. 97). It was observed that the dogs with slight trauma had significantly (P<0.05) higher mean scores on days 7, 15, 30. Although the gait scores on 45th day for slight, moderate and severe trauma cases were at par with each other.

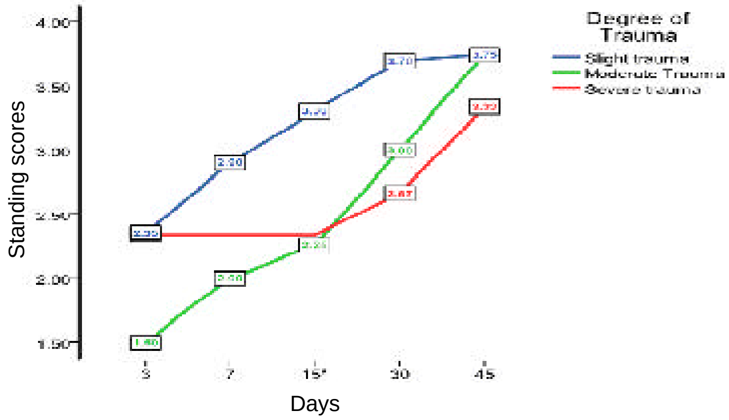


Fig. 97: *Mean ± SE values of standing scores in animals with various degree of trauma on different days.*

Gait scores at walking: The gait scores for walking during the follow-up period between 3 and 45 days for different groups with respect to the fixator type (Fig. 98), sex of animal (Fig. 99), experimental groups (Fig. 100), cause of injury (Fig. 101), time since injury (Fig. 102), type of wound (Fig. 103), and bone involved (Fig. 104) did not differ significantly (P>0.05).

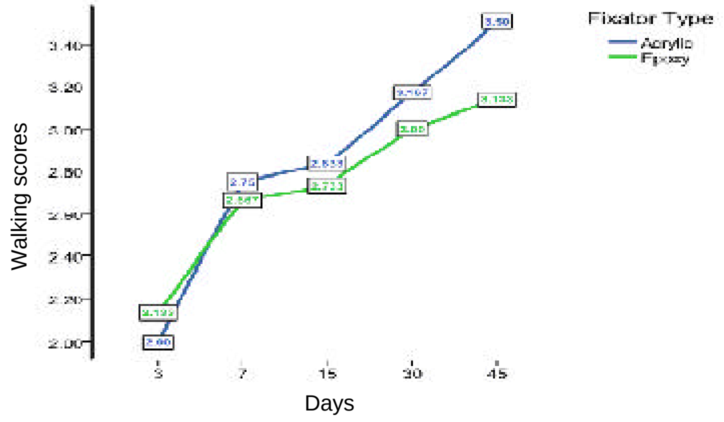


Fig. 98: *Mean ± SE values of walking scores in animals of acrylic and epoxy fixator groups on different days.*

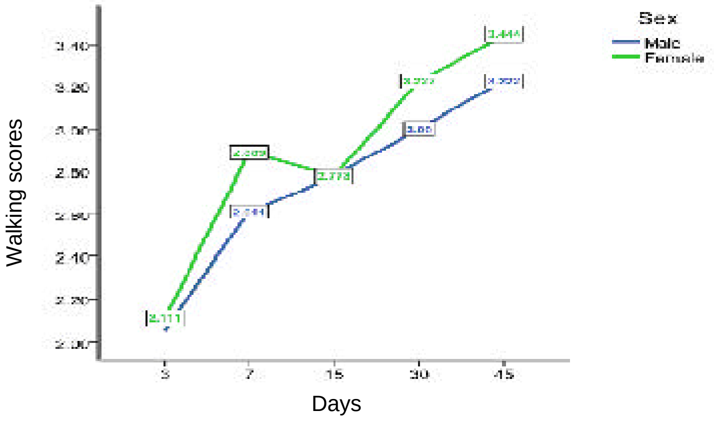


Fig. 99: *Mean ± SE values of walking scores in male and female animals on different days.*

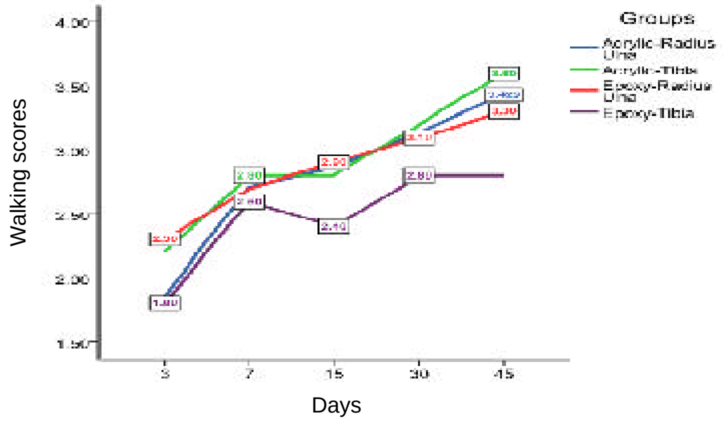


Fig.100: *Mean ± SE values of walking scores in animals of different treatment groups on different days.*

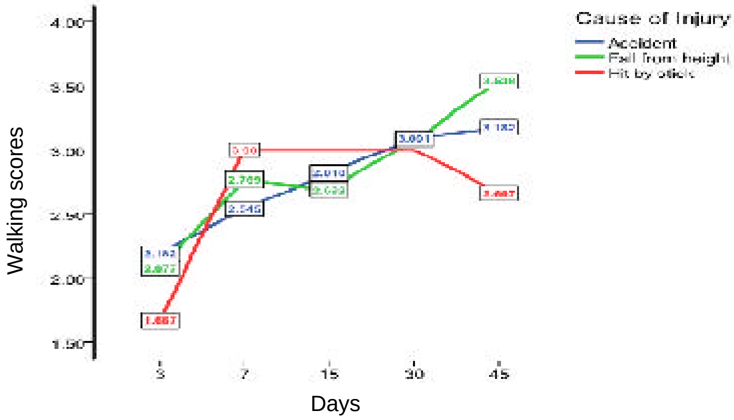


Fig.101: *Mean ± SE values of walking scores in animals with different causes of injury on different days.*

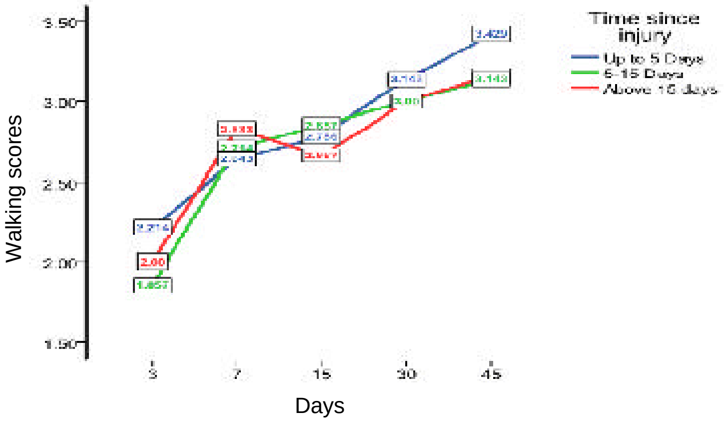


Fig. 102: *Mean ± SE values of walking scores in animals brought for treatment on different days of injury.*

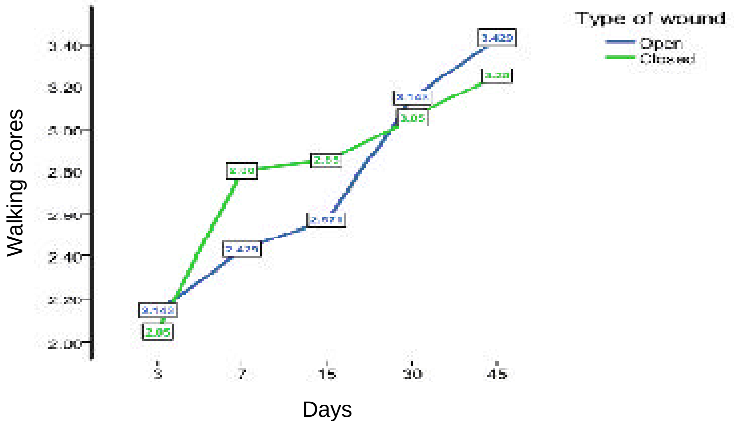


Fig. 103: *Mean ± SE values of walking scores in animals with open and closed fractures on different days.*

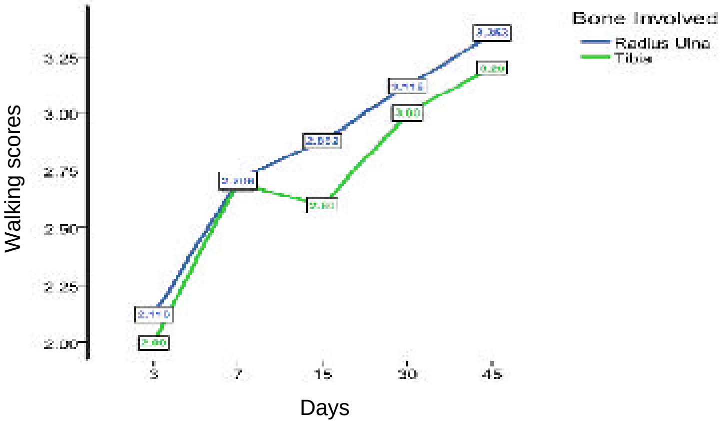


Fig.104: *Mean ± SE values of walking scores in animals with fractures of R/U or tibia on different days.*

Significant differences (P<0.05) were observed in the gait scores for walking during the follow-up period between different groups with respect to the variables like age group, weight group and degree of trauma.

The mean gait score during walking for animals above 2 years on days 3 and 7 were significantly (P<0.05) lower than those aged 6-12 months and 1-2 years and was at par with the animals aged 0-6 months (Fig. 105). There was no difference in the mean gait scores on days 15, 30 and all the age groups were at par with each other. On day 45, mean scores of 0-6 month and 6-12 month age groups were significantly (P<0.05) higher than 1-2 year and above 2 year age group animals.

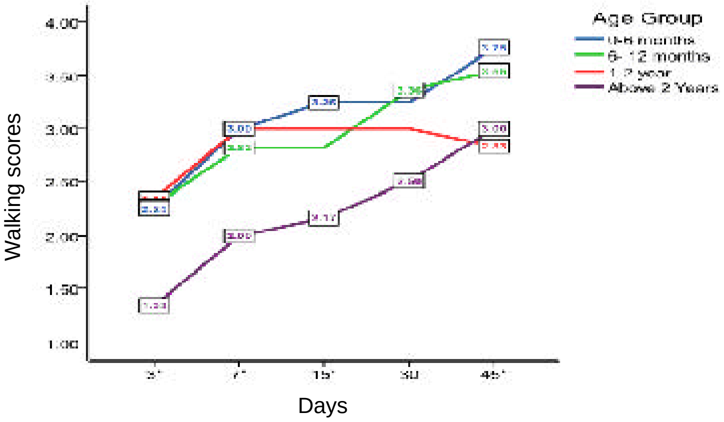


Fig. 105: *Mean ± SE values of walking scores in animals of various age groups on different days.*

Treated cases were also analyzed with respect to the weight groups. First group (up to 10 kg body weight), second (10-20 kg) and third (above 20 kg) groups had 6, 13 and 8 animals, respectively (Fig. 106). The mean gait score for the animals weighing up to 10 kg was higher on days 7, 15, 30 and 45. The mean score for gait on day 45 for the animals up to 10 kg was significantly (P<0.05) higher than the animals weighing above 20 kg.

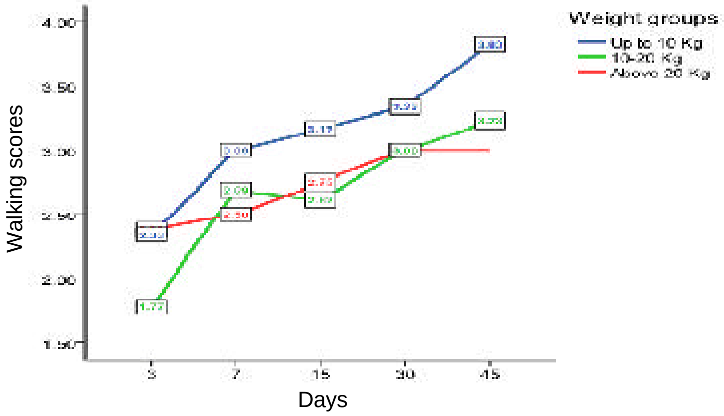


Fig. 106: *Mean ± SE values of walking scores in animals of different weight groups on different days.*

Analysis of gait with respect to the degree of trauma was done by grouping the animals having slight, moderate and severe soft tissue trauma (Fig. 107). The mean gait score on day 7 in animals having slight trauma was significantly (P<0.05) higher than those with severe trauma. However, no significant differences in the mean scores were observed on days 3, 15 30 and 45.

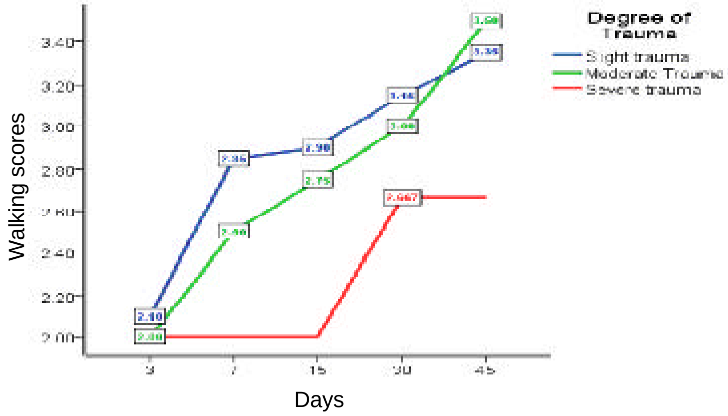


Fig. 107: *Mean ± SE values of walking scores in animals with different degrees of trauma on different days.*

Gait scores at running: The gait scores for running during the follow-up period between 3 and 45 days for different groups with respect to the fixator types (Fig. 108), age groups (Fig. 109), sex of the animals (Fig. 110), treatment groups (Fig. 111), cause of injury (Fig. 112), time since injury (Fig. 113), type of wound (Fig. 114) and bone involved (Fig. 115), did not differ significantly (P>0.05).

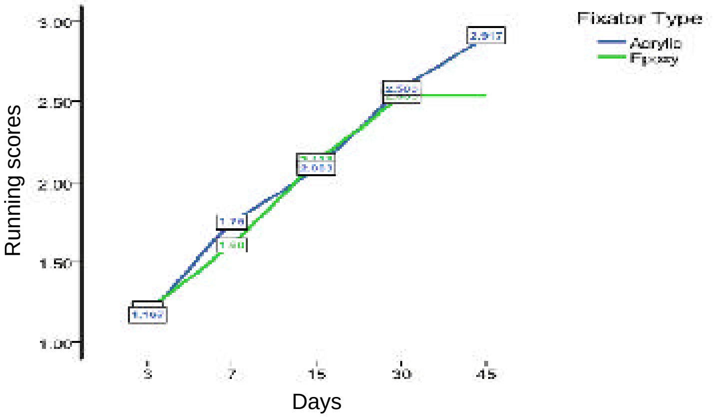


Fig. 108: *Mean ± SE values of running scores in animals of acrylic and epoxy groups on different days.*

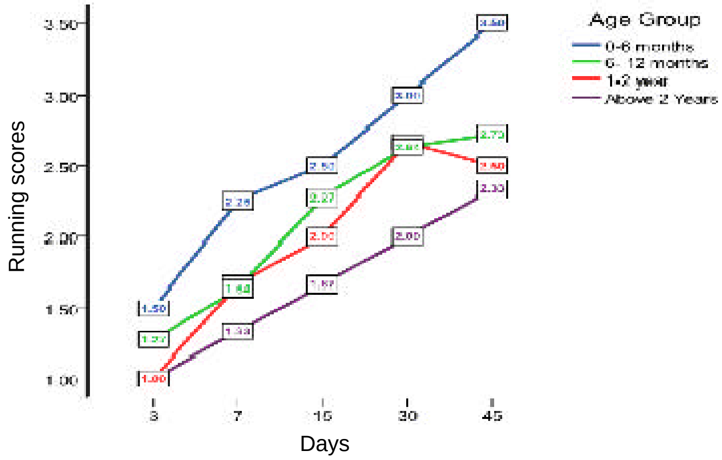


Fig. 109: *Mean ± SE values of running scores in animals of various age groups at different days.*

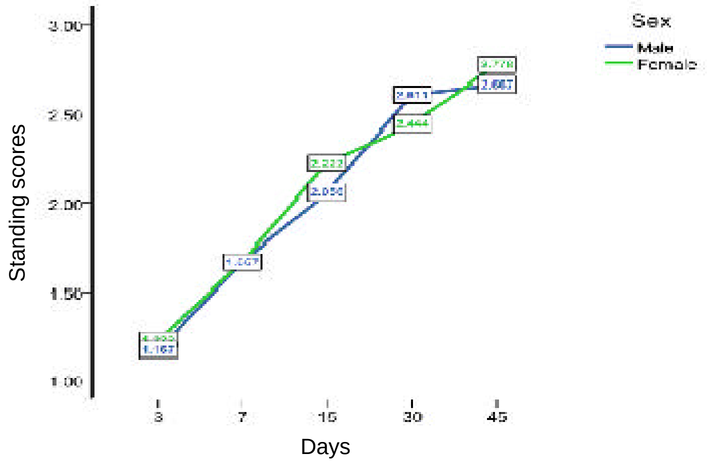


Fig. 110: *Mean ± SE values of running scores in male and female animals on different days.*

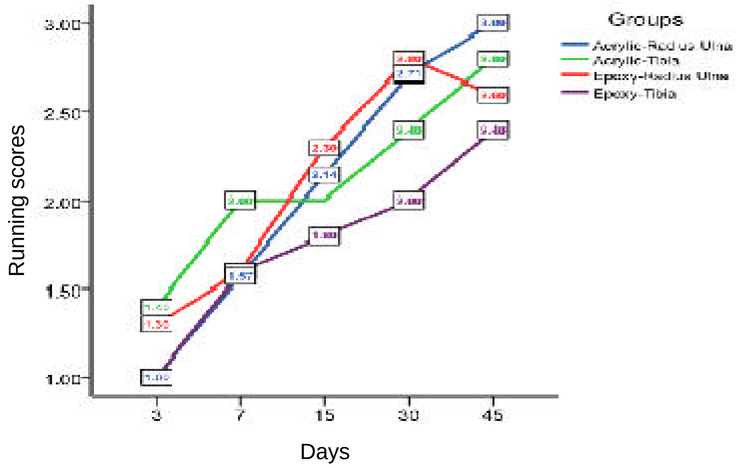


Fig. 111: *Mean ± SE values of running scores in animals of different treatment groups on different days.*

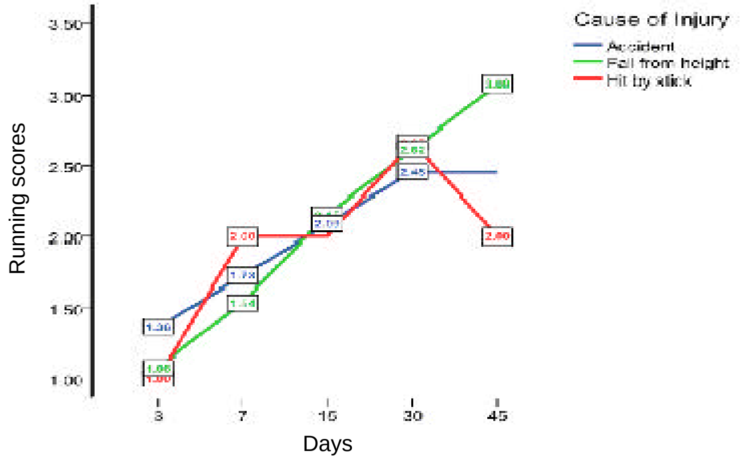


Fig. 112: *Mean ± SE values of running scores in animals with different causes of injury on different days.*

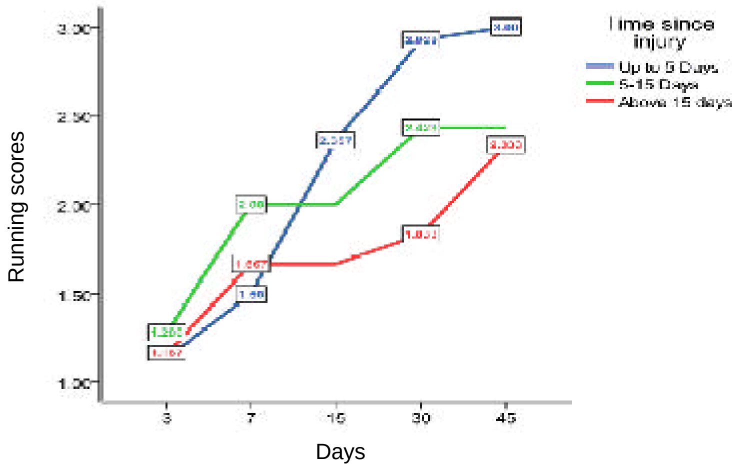


Fig.113: *Mean ± SE values of running scores in animals brought for treatment on different days of enjury.*

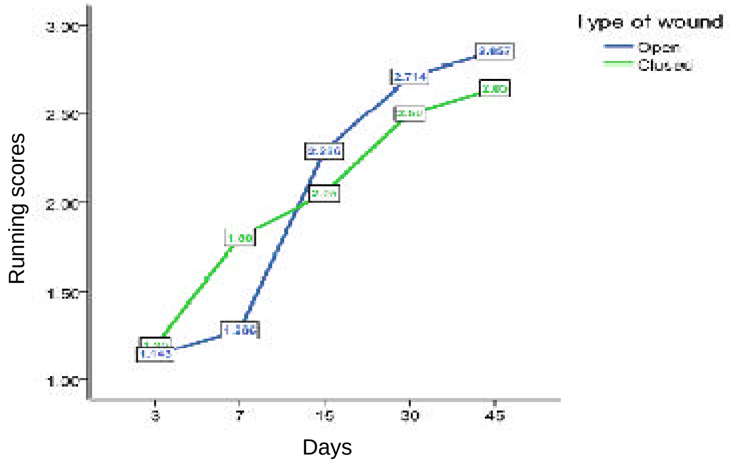


Fig. 114: *Mean ± SE values of running scores in animals with open and closed fractures on different days.*

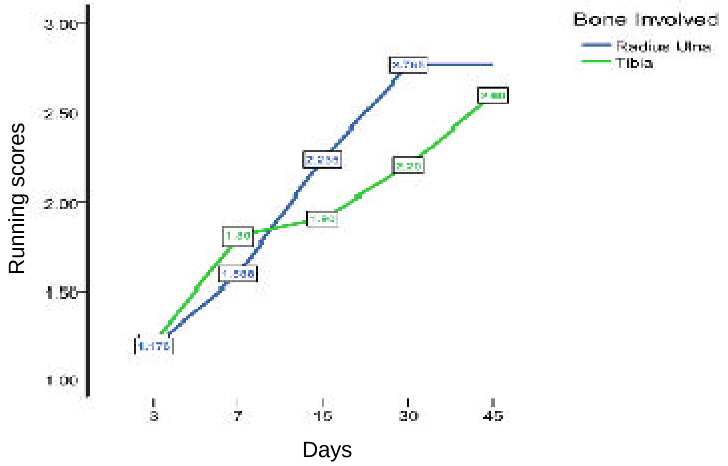


Fig. 115: *Mean ± SE values of running scores in animals with fractures of R/U or tibia on different days.*

Significant differences were observed in the gait scores between different groups with respect to the weight groups and degree of trauma.

According to the weight, the animals were grouped as first group (up to 10 kg body weight), second (10-20 kg) and third (above 20 kg) groups with 6, 13 and 8 animals, respectively (Fig. 116). The mean gait scores in the animals weighing up to 10 kg were higher on days 3, 15, 30 and 45. The mean gait score for running on day 45 for the animals weighing up to 10 kg was significantly (P<0.05) higher than the animals weighing 10-20 kg or above 20 kg.

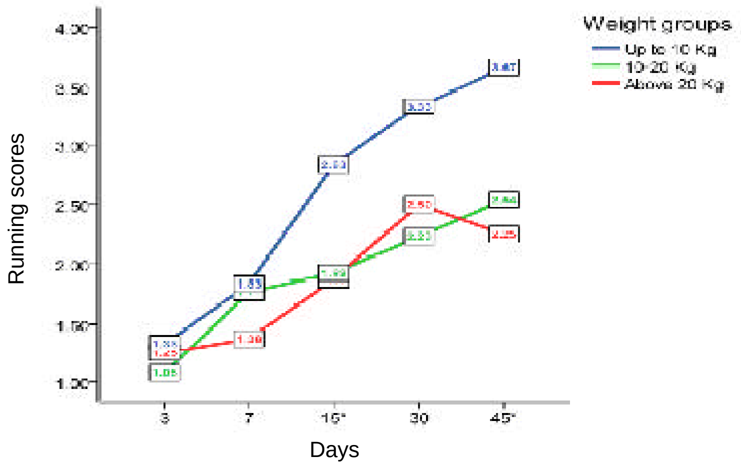


Fig. 116: *Mean ± SE values of running scores in animals of various weight groups on different days*

According to the degree of trauma, the animals were grouped with slight, moderate and severe soft tissue trauma (Fig. 117). The mean scores on day 7 in animals having slight trauma was significantly (P<0.05) higher as compared to those with severe trauma, however, no significant differences in the mean scores were observed at other intervals.

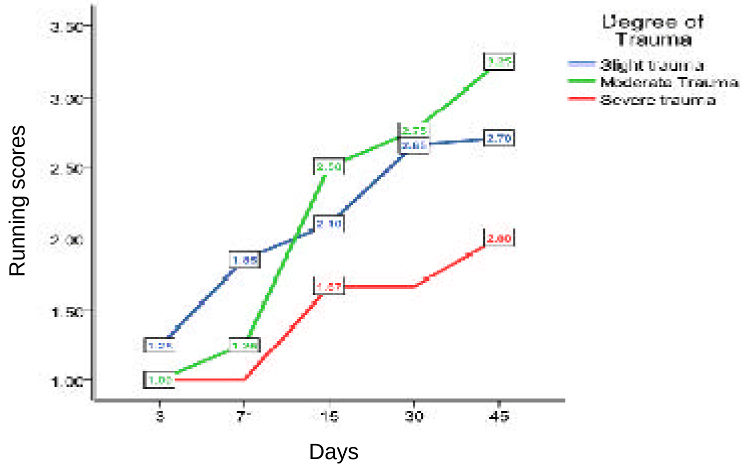


Fig. 117: *Mean ± SE values of running scores in animals with different degrees of trauma on different days.*

Microbiological examination

The result of the antibiotic sensitivity test has been shown in fig 118. Ampicillin + sulbactum was the most sensitive antibiotic in 60 % samples, followed by gentamicin (25 %), tetracycline (10 %) and laevofloxacin (5 %).

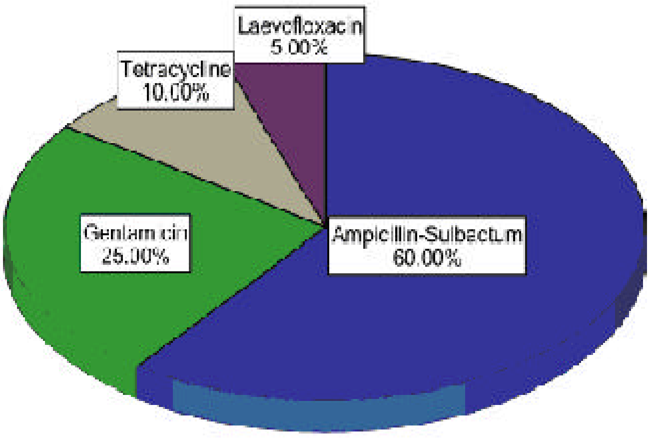


Fig. 118: *Antibiotics found effective during sensitivity test.*

Haemato-biochemical observations

Haemoglobin (Hb) : The overall mean ± SE values of Hb on days 0, 7, 15, 30 and 45 were 10.24 ± 0.35, 10.37 ± 0.40, 10.41 ± 0.29, 10.46 ± 0.28 and 10.80 ± 0.23 g/L, respectively. There was no significant (P>0.05) difference in the values of Hb at different time intervals between the groups.

Packed cell volume (PCV) : The overall mean ± SE values of PCV on days 0, 7, 15, 30 and 45 were 31.15 ± 1.55, 32.93 ± 1.12, 33.07 ± 1.10, 31.93 ± 0.92 and 34.56 ± 0.95 %, respectively. There was no significant (P>0.05) difference in the values of PCV at different time intervals between the groups.

Calcium : The overall mean ± SE values of calcium on days 0, 7, 15, 30 and 45 were 2.44 ± 0.05, 2.54 ± 0.05, 2.44 ± 0.05, 2.43 ± 0.05 and 2.44 ± 0.05 mmol/L, respectively. There was no significant (P>0.05) difference in the values of calcium at different time intervals between the groups.

Phosphorus : The overall mean ± SE values of phosphorus on days 0, 7, 15, 30 and 45 were 1.20 ± 0.04, 1.19 ± 0.03, 1.18 ± 0.02, 1.23 ± 0.03 and 1.16 ± 0.02 mmol/L, respectively. There was no significant (P>0.05) difference in the values of phosphorus at different time intervals between the groups.

Alkaline Phosphatase : The overall mean ± SE values for AKP on days 0, 7, 15, 30 and 45 were 189.00 ± 4.58, 190.93 ± 4.41, 192.81 ± 4.47, 188.30 ± 4.48 and 191.11 ± 4.32 U/L, respectively. There was no significant (P>0.05) difference in the values of AKP at different time intervals between the groups.

Radiographic observations

Various radiographic findings have been summarized in the Table 7. Radiographs were taken immediately after surgery and follow-up radiographs were taken till radiographic fracture healing was observed. Very good and good reduction of fracture fragments was observed in 29.63 % and 51.85 % cases, respectively. In the remaining 18.52 % cases, satisfactory fixation was observed (Fig. 119). Postoperative radiographs showed slight overriding of fracture fragments in six cases.

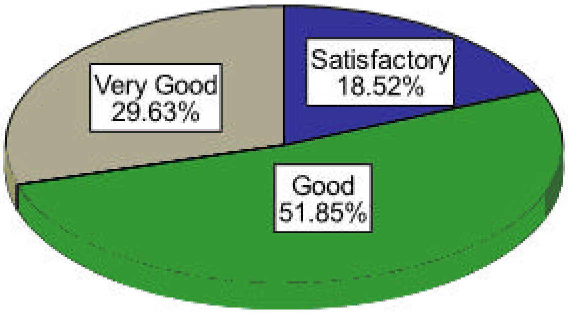


Fig. 119: *Level of fixation in animals treated with ESF.*

Animals treated with acrylic fixators showed very good, good and satisfactory level of fixation in 20, 60 and 20 % of cases, respectively (Fig. 120).

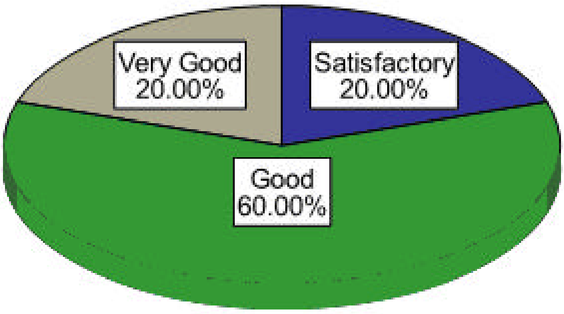


Fig. 120: *Level of fixation in animals of acrylic group.*

Animals treated with epoxy fixators showed very good, good and satisfactory level of fixation in 41.67, 41.67 and 16.67 % of cases, respectively (Fig. 121).

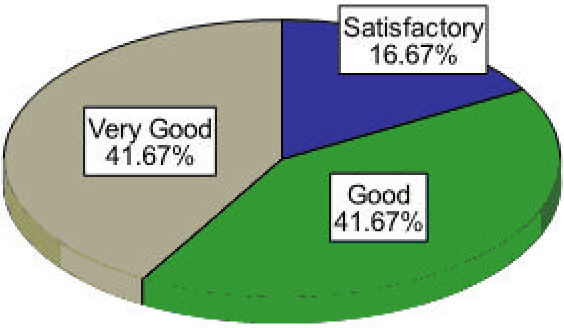


Fig. 121: *Level of fixation in animals of epoxy group.*

Radiographs revealed that epoxy material was highly radiodense, whereas acrylic was radiolucent. Hence visualization of bone, fracture site in particular, was clearer with acrylic fixators (Fig. 122).

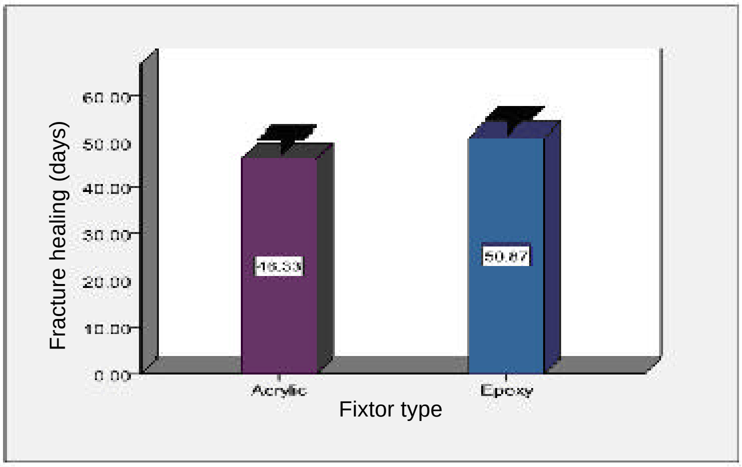


Fig 123: *Mean ± S.E. time for fracture healing (days) in animals treated with acrylic and epoxy fixators.*

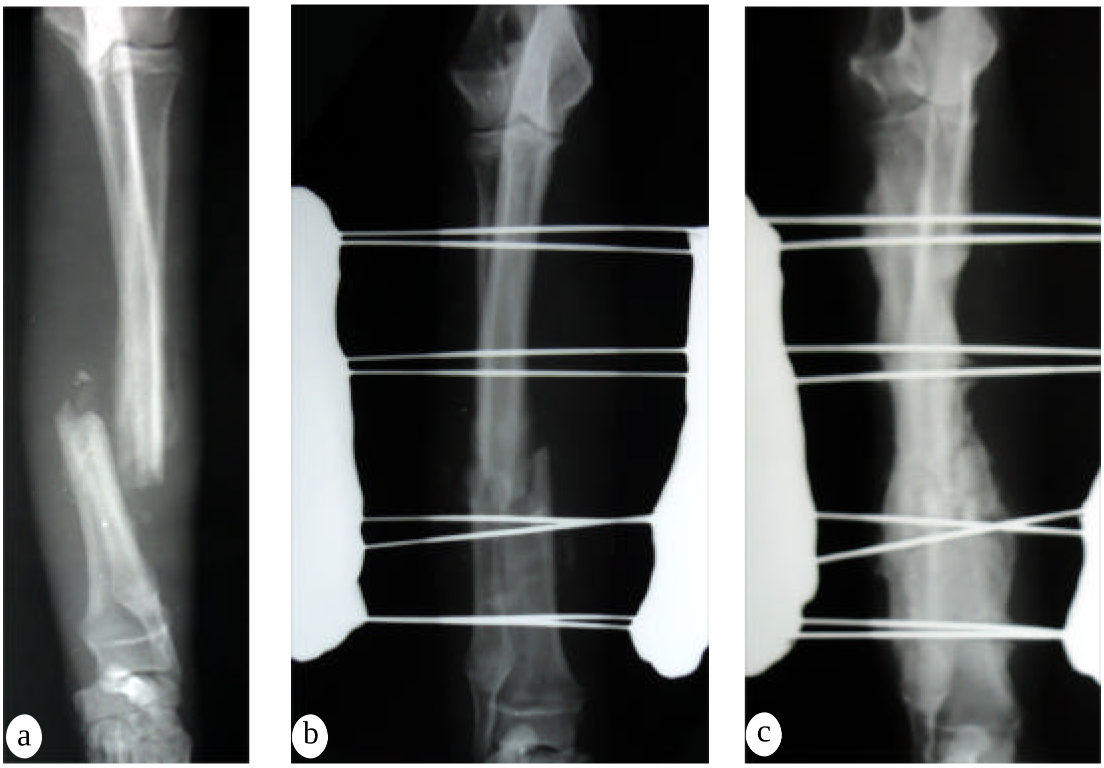


Fig. 122A : *Preoperative (a); immediate postoperative (b) and follow up radiographs (c) of case with radius / ulna fracture treated with epoxy ESF.*

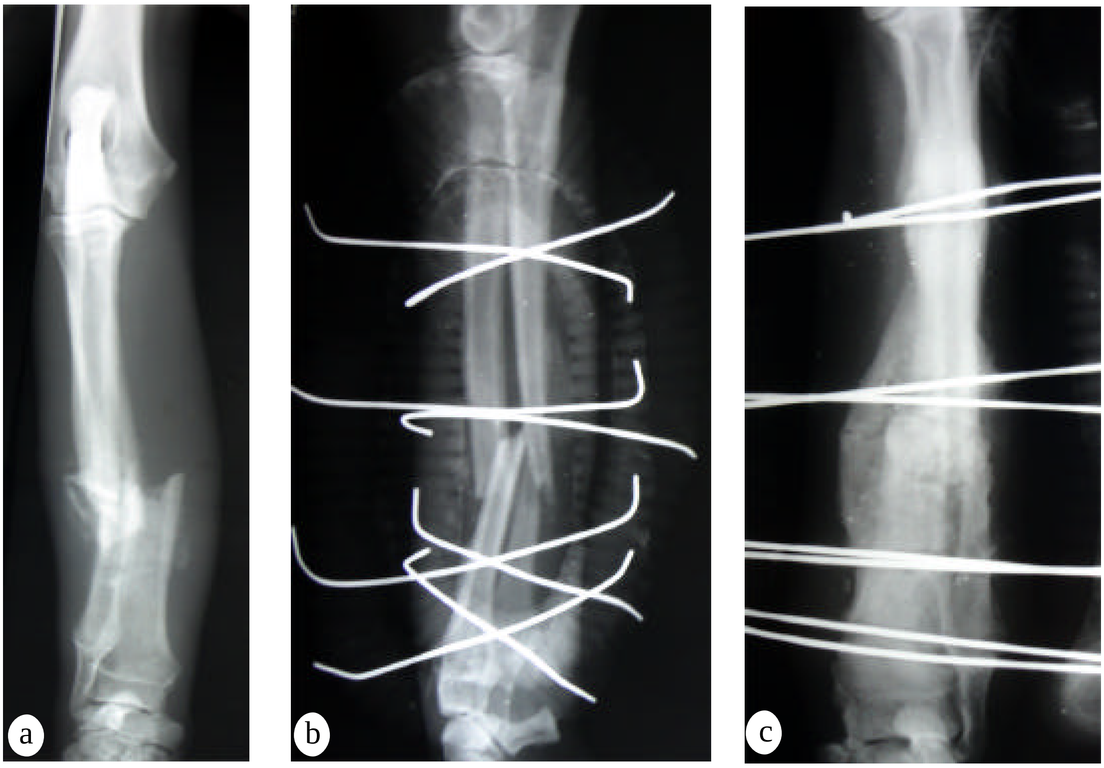


Fig. 122B: *Preoperative (a); immediate postoperative (b) and follow up radiographs (c) of case with radius / ulna fracture treated with acrylic ESF.*

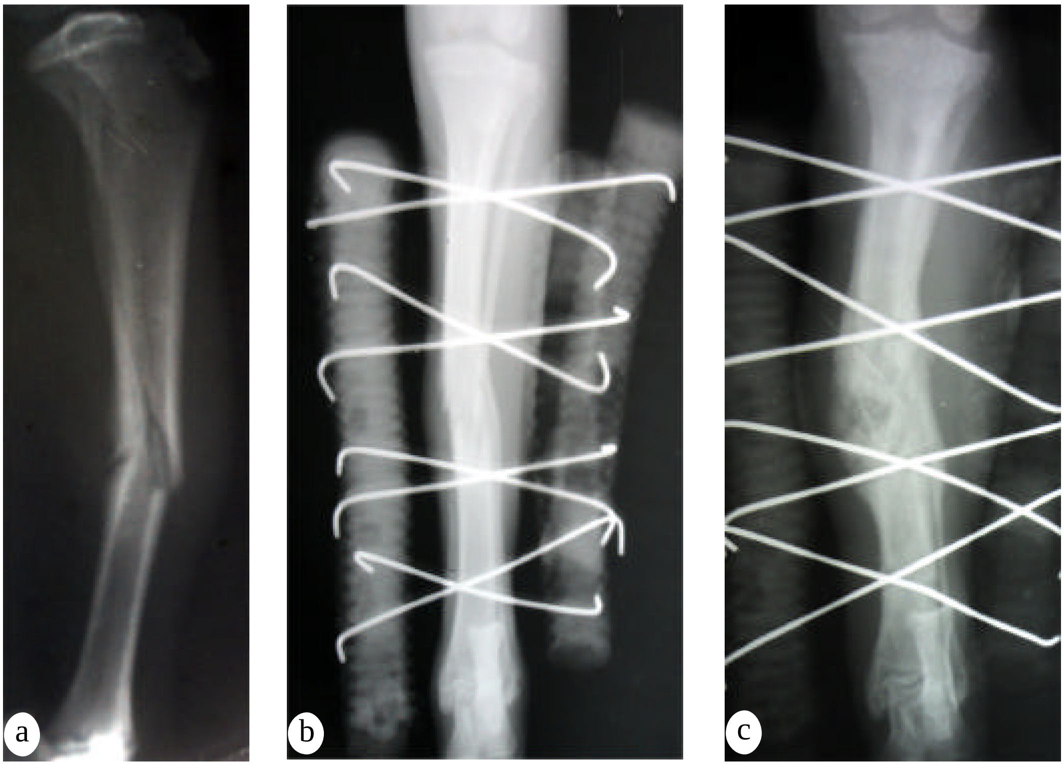


Fig. 122C : *Preoperative (a); immediate postoperative (b) and follow up radiographs (c) of case with tibia/fibula fracture treated with acrylic ESF.*

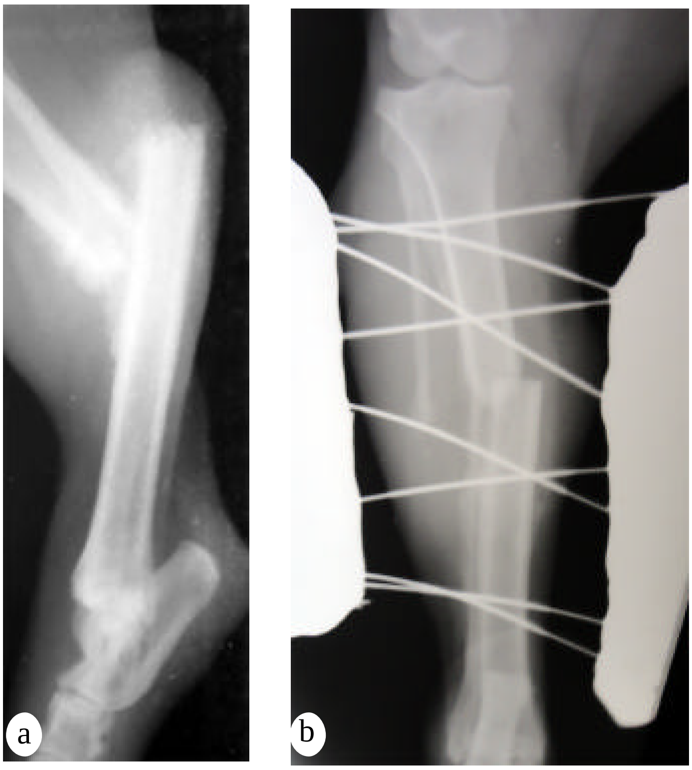


Fig. 122D: *Preoperative (a) and postoperative (b) radiographs of case with tibia/fibula fracture treated with epoxy ESF.*

None of the pins was broken (except in one case, where one distal most pin was broken as reported on day 45). Callus formation started as early as on day 15. In one case delayed healing was seen and callus formation started after 30 days (11 year old animal).

The fixators were removed after radiographical healing i.e., bridging callus was observed. The mean ± SE days for radiographic healing in acrylic R/U and T/F group were 46.14 ± 4.72 and 46.6 ± 7.08, respectively. In epoxy R/U and T/F groups, the time required for fracture healing was 49.8 ± 4.73 and 53.00 ± 4.90 days, respectively. The mean ± SE time required for fracture healing including animals of all groups was 48.85 ± 2.56 days.

There was no significant effect of factors like fixator type (acrylic or epoxy) (Fig. 123), breed involved (Fig. 124), sex (Fig. 125), treatment group (Fig. 126), weight of the animal (Fig. 127), cause of injury (Fig. 128), time since injury (Fig. 129), type of fracture (Fig. 130), degree of trauma (Fig. 131) or bone involved (Fig. 132) on the fracture healing.

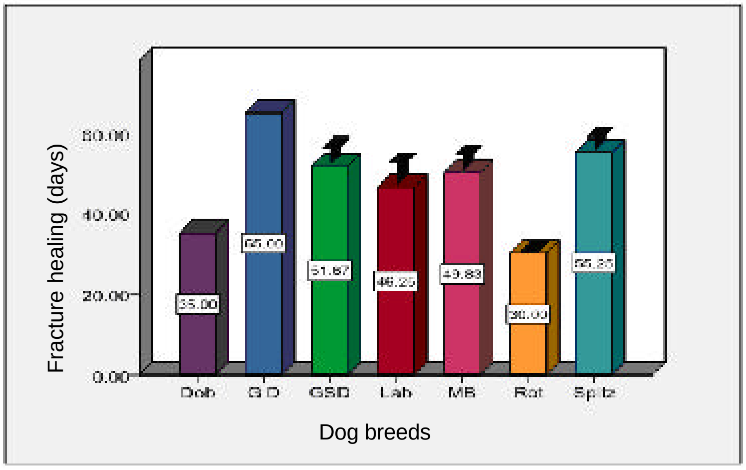


***Fig 124:** Mean ± S.E. time for fracture healing (days) in dogs of different breeds.*

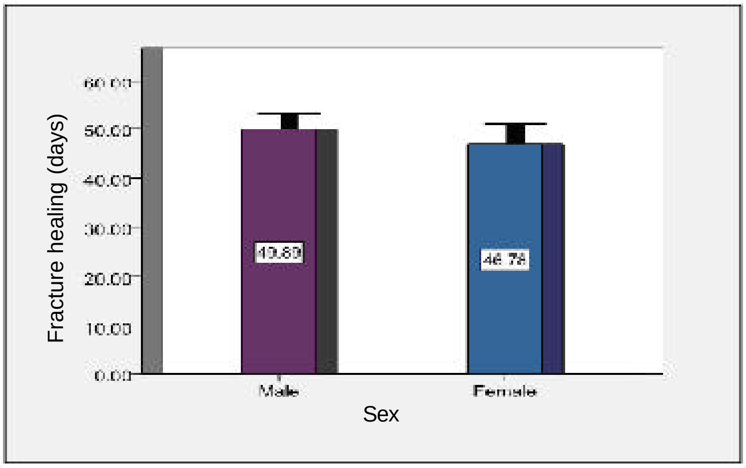


***Fig 125:** Mean ± S.E. time for fracture healing (days) in male and female animals.*

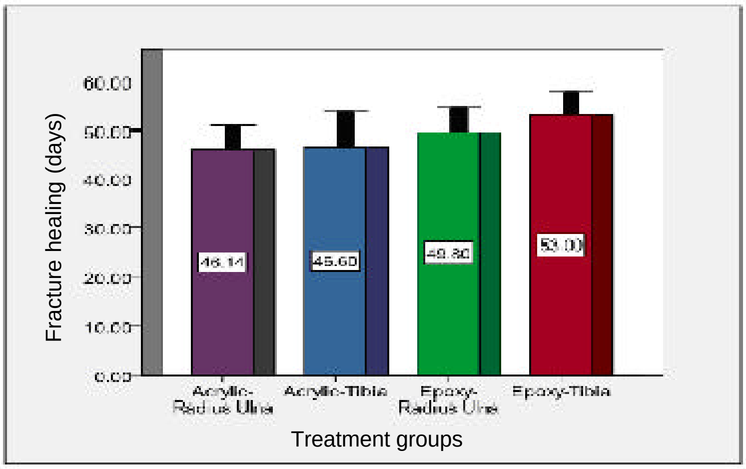


Fig 126: *Mean ± S.E. time for fracture healing (days) in animals of different treatment groups.*

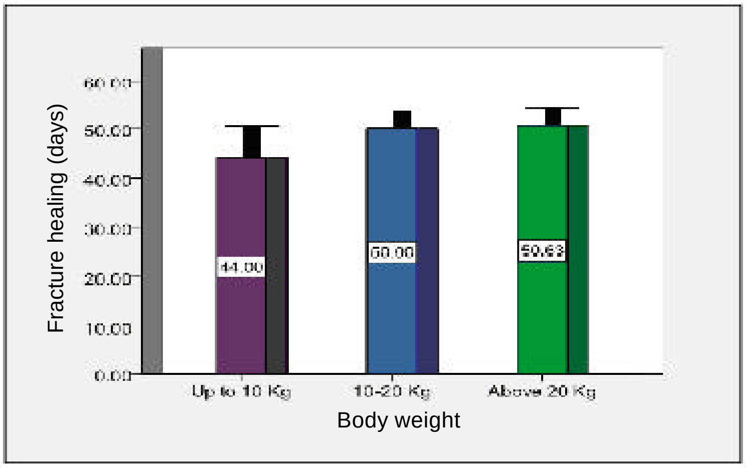


Fig 127: *Mean ± S.E. time for fracture healing (days) in animals with different body weight (kg).*

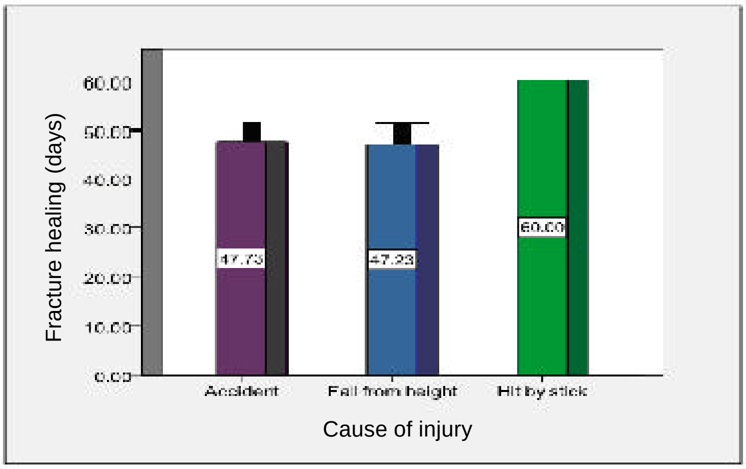


Fig 128: *Mean ± S.E. time for fracture healing (days) in animals with different causes of injury.*

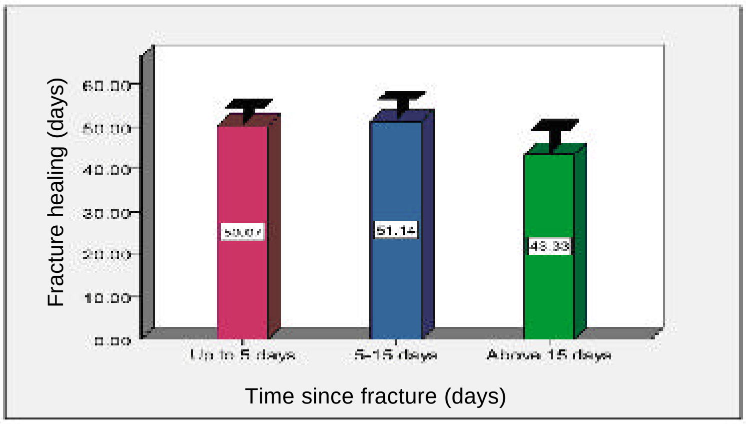


Fig 129: *Mean ± S.E. time for fracture healing (days) in animals brought for treatment on different days of injury.*

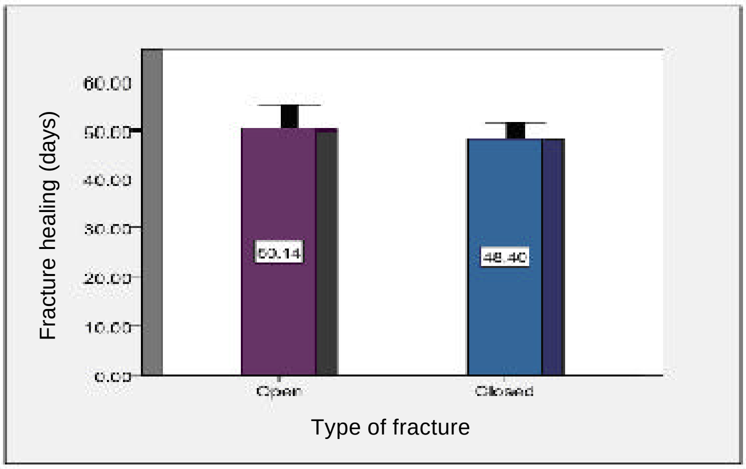


Fig 130: *Mean ± S.E. time for fracture healing (days) in animals with open and closed fractures.*

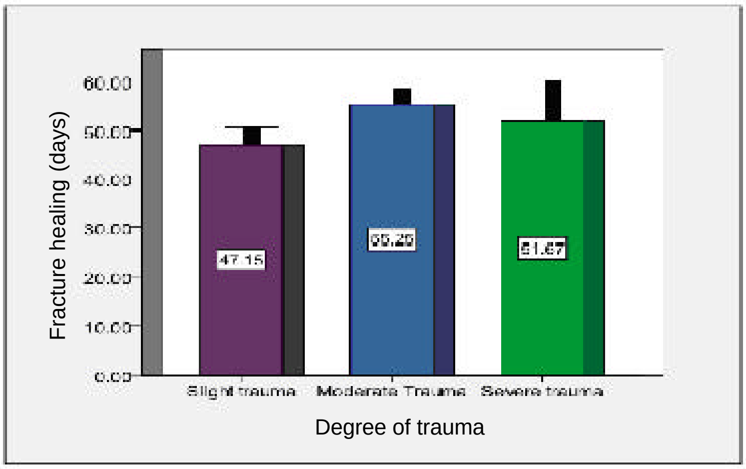


Fig 131: *Mean ± S.E. time for fracture healing (days) in animals with different degrees of trauma.*

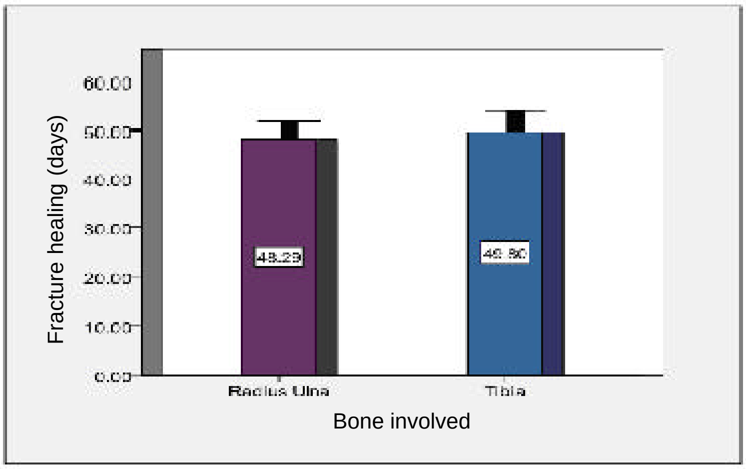


Fig 132: *Mean ± S.E. time for fracture healing (days) in animals with fractures of radius/ ulna or tibia.*

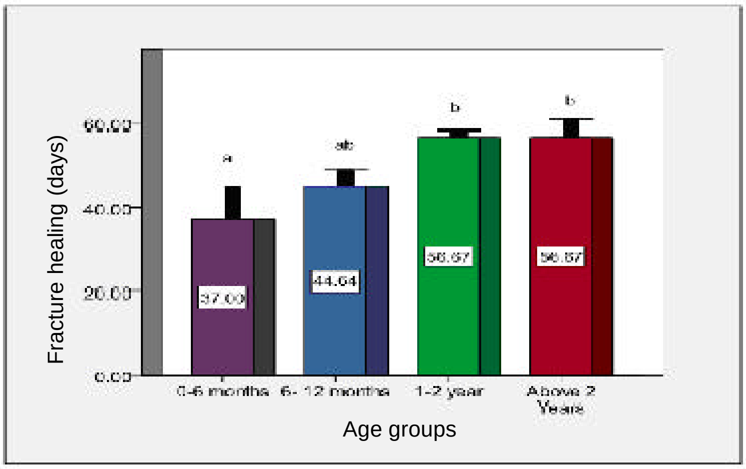


Fig 133: *Mean ± S.E. time for fracture healing (days) in animals of different age groups.*

But age of the animal had a significant effect on fracture healing (Fig. 133). The mean ± SE days for fracture healing in animals of 0-6 months age group was 37.00 ± 7.68, whereas it was 44.64 ± 4.09, 56.67 ± 1.67 and 56.67 ± 4.01 days in animals of 6-12 months, 1-2 year and above 2 years age groups, respectively. Fracture healing was significantly ($P<0.05$) faster in animals aged 0-6 months as compared to animals of 1-2 years and above 2 years of age.

Functional recovery

Overall, in the present study 62.96 % dogs showed very good functional recovery, and it was good in 29.63 % cases. Satisfactory functional recovery was observed in remaining 7.41 % animals (Fig. 134).

Fig. 134: *Functional recovery in animals treated with acrylic and epoxy fixators.*

Fig. 135 : *Functional recovery in animals treated with acrylic fixators.*

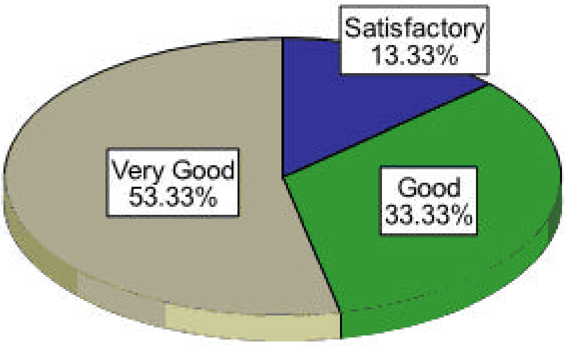


Fig. 136: *Functional recovery in animals treated with epoxy fixators.*

Functional recovery was very good (75 %) to good (25) in animals treated with acrylic fixators (Fig. 134).

In animals treated with epoxy fixators, functional recovery was very good, good and satisfactory in 53.33, 33.33 and 13.33 % cases, respectively (Fig. 135).

❑❑❑

DISCUSSION

External fixators are primarily used for fracture treatment but may also be used for deformity correction and arthrodesis, among other applications (Harari, 1992; Aron *et al.,* 1995; Lewis *et al.,* 2001). External skeletal fixation is useful as it promotes the biological environment of the fracture site. By proper placement of the external fixator pin, the amount of trauma to the soft tissues and disturbance to the blood supply of a fracture are reduced, which promotes earlier tissue differentiation and vascularization (Egger, 1983; Ueng *et al*., 1999; White, 1999; Lewis *et al.,* 2001).

Transarticular application of ESF has been used in small animal practice for arthrodesis, temporary immobilization of joints for treatment of injuries at proximal or distal ends of the long bones (Toombs *et al*., 1989; Anderson and Constantinescu, 1998; Owen, 2000). Paley *et al*. (1990) have used external skeletal fixators for limb lengthening procedures.

Lincoln (1992) stated that ESF is useful in treatment of open fractures, delayed union and non union fractures in small animals. External skeletal fixators may be applied using either closed or open fracture reduction and are often used for highly comminuted fractures that cannot be reconstructed anatomically (Dudley *et al*., 1997; Lauer *et al*., 2000). Haas *et al*. (2001) and Laverty *et al*. (2002) have reported the use of ESF in the treatment of distal radial and ulnar fractures in small animals and found it to be a satisfactory and appropriate treatment providing sufficient stability with minimal soft tissue trauma. Clarke and Carmichael (2006) have treated distal diaphyseal fractures of tibia and radius using hybrid external skeletal fixator on three dogs.

Connecting rods, or sidebars, provide a bridge between the pin clamps and rings, unifying the bony fragments in the external fixator construct. Sidebars, traditionally, have been composed of stainless steel, aluminum alloy or carbon fiber (Podolsky and Chao, 1993). An ideal sidebar should be stiff, lightweight and radiolucent for radiographic evaluation. In addition to higher stiffness, carbon fiber connecting rods have the advantage of being radiolucent. But the carbon fiber is costly and cannot be reused (Podolsky and Chao, 1993; Lewis *et al.*, 2001). Stainless steel or other metallic bars are very heavy and costly when compared to free form of fixators i.e., fixators with polymer components.

Polymers used in veterinary external fixation include methylacrylates and epoxy putties (Worth, 2007). These polymers are light in weight, stiff, easily available and cost effective. A number of different compounds have been used to form the connecting bar for free-form fixators, most are methylmethacrylate based (dental or hoof acrylics or cement used for implantation of prostheses (Roe and Keo, 1997).They have been used and studied as replacement material of stainless steel connecting bars and clamps, because of their low cost, simplicity and adaptability to various pin diameters (Okrasinski *et al*., 1991; Martinez *et al*., 1997; Roe and Keo, 1997; McCartney, 1998; Shahar, 2000; Christoph *et al*., 2003; Chandy *et al*., 2007; Julie *et al*., 2007; Worth, 2007; Kumar *et al*., 2011). Epoxy had been used as fixator clamp (Staudte *et al.*, 2004). Roe and Keo (1997) have suggested that epoxy compound can replace methyl acrylates.

A variety of acrylics (medical grade) are available in the market, dental and bone cement acrylic being the commonly available. Dental acrylic is relatively easily available and more economical, so was used in the present study. A number of epoxy putty (industrial grade) is available in the market. Because of the easy availability of M-seal® (Pidilite Industries Ltd., Daman, India) in the market and better handling characters, it was selected in the present study.

During standardization, all the three types of M-seal available in the market viz. regular (red), fast curing (blue) and quick set (white) were tested. It was found that the regular M-seal took very long time to set (more than 80 min), whereas, the fast curing M-seal took about 20-25 min for setting. Further, the time of setting for quick set M-seal was less than 10 min, not giving enough time to mould and form the construct. Hence, on the basis of the time taken for setting, fast curing M-seal was choosen and used for the construction of different designs of epoxy-pin fixators.

In the present study the comparison of acrylic and epoxy fixators was done under different phases. Firstly, the procedure to form the constructs was standardized on the plastic rods and the technical easiness or difficulties, their weight and economy was studied. In the second phase, their mechanical properties were studied by *in vitro* tests. This was followed by the third phase in which the clinical use and safety was evaluated.

Part 1: Development of different designs of acrylic and epoxy-pin external skeletal fixation systems

Construction of the designs

Earlier studies on biomechanical testing on ESF constructs have used either bone or bone replacement materials. Plastic pipes and hard wood dowels have been used for construction and comparison of ESF constructs (Okraninski; 1991; Lewis *et al.*, 2001; David and Nirmal, 2003; Kowaleski *et al.*, 2003; Alan *et al.*, 2004).

Okrasinski (1991) had used hardwood dowels of 2.23 cm diameter and 23 cm length as bone replacement material for biomechanical studies. During testing the wood dowels split before the ESF failed. Kowaleski *et al.* (2003) have also used wood dowels of 22.5 cm diameter and 5 cm length.

Various plastic pipes made of ultra high density polyethylene (UHDPE) have been used as a bone replacement for ESF constructs in various studies. Nineteen mm thick Delerin rods have been used in biomechanical testing of ESF constructs by Lewis *et al.* (2001) and White *et al.* (2003). Solid Acetal rods of 22 mm diameter and 25 cm length were used by Alan *et al.* (2004).

In the present study, UHDPE pipes of 20 mm diameter were used to form ESF constructs. These rods of uniform diameter offered the advantage of reducing variation in the experimental design, due to different size of bones in terms of length and diameter. In addition, the mineral content and hardness of bones vary with the breed, age, sex, weight and condition of the dog. So, by using the rods, these variations which could alter and affect the results of the experiment could be minimized.

K-wires of 1.5-2.0 mm diameter were most commonly used in humans (Kummer, 1992; Lewis *et al.*, 1998). Whereas in dogs and cats, 1-1.6 mm K-wires were used most commonly (Ferriti, 1991) in external fixators. Kumar *et al.* (2011) have suggested that 1.5 mm diameter K-wires were most suited for treatment of fracture in dogs. Hence, in the present study, K-wires of 1.5 mm diameter were used for the development of constructs. To reduce the variation, same diameter K-wires were used in all the designs of fixators.

The angle of insertion between pins attached to the external frame affects its biochemical properties (Lewis *et al*., 1998). The angle between opposing pins should be close to 90° to maximize stability and minimize shear (Paley, 1991). Craniocaudal bending stiffness was reported to decrease significantly when the pin intersection angle decreased from 90° to 45°. Hence in the present study, to minimize the variation between the designs, the pins were crossed to each other at 90° angle in multiplanar and circular designs.

The position of bone within the ESF frame (centre or eccentric) also affects the fixation rigidity. Moving bone off centre in fixator rings decreases its torsional stiffness (Fleming *et al*., 1989). Hence in this study, in all the fixators the plastic rods were placed at a centric position within the fixator construct to minimize variations.

Shahar (2000) suggested a minimum diameter of acrylic column should be 19.1 mm if used as a substitute of connecting bar of Kirschner apparatus for animals weighing 12 to 45 kg. In the present study, 20 mm diameter of acrylic and epoxy columns were used as connecting side bars and rings. The diameter of side bars was kept constant for all the designs of fixator constructs.

The application of acrylic fixator was relatively more difficult than epoxy fixator. The acrylic had to be mixed just before application, with continuous stirring, to maintain a flowing consistency. When delayed during application, it became hard and it had to be discarded and fresh mix had to be prepared. Handling of acrylic was difficult particularly as it could leak from the points of pin insertion. When the room temperature was relatively higher (>20-21 °C), the mixing glass beaker had to be pre-cooled (to prevent early setting). The liquid contains methyl methyl acrylate polymer, which forms poly methyl methyl acrylate (PMMA), which was highly flammable, it had to be kept away from the source of ignition. Anderson (1988) reported that the fumes produced during polymerization are noxious and toxic. In the present study also during mixing of acrylic powder with liquid, fumes were produced, which were quite irritating to eyes, respiratory system and skin. After pouring the acrylic into the pipes, it took about 11 min for polymerization and hardening during which a lot of heat was produced, and care had to be taken to prevent skin burns. Martinez *et al*. (1997) also reported such type of complications related to the use of acrylic. In contrast, the heat produced during hardening of epoxy material was very less. This could be due to the fact that epoxy took relatively long time for polymerization and hence must have dissipated gradually.

Epoxy also had to be prepared immediately before the use. The epoxy monomer was mixed with the resin, till it acquired a uniform colour of dough. If a pin is pushed into the epoxy dough, a cavity forms in the epoxy putty, and it does not contact the entire pin surface, so it is necessary to squeeze the epoxy putty around the pin (Roe and Keo, 1997). A similar procedure was followed in the present study to ensure that epoxy putty made a good contact with the pin surface.

The time required to apply the fixator (excluding the hardening time) was significantly lower with epoxy (13.6 min) than acrylic (20.32 min). Among different designs, the mean time required to construct uniplanar design was the least, followed by multiplanar designs and circular design, in both acrylic and epoxy fixator constructs. Especially for acrylic circular design, the time required for constructing circular rings, it's joining with side bars, centering of the UDHPE rods and sealing of various joints took relatively longer time.

Time for hardening was lower with acrylic fixators. The polymerization of polymethylmethacrylate involves three stages: dough time, working time and setting time (Hall, 1981; Mascia, 1982). The dough time occurs within the first 3 min, and the result is a material that is soft, pliable, and has the consistency of a plastic. Depending on the ambient temperature, the working time can vary in length up to the setting time of 12 to 15 min. The warmer the environment, the faster the material will set (Hall, 1981; Mascia, 1982). In the present study also, during warm climate (summer) the acrylic hardened within 10-12 min. At low temperature (winter season) acrylic took more than 20 min to harden. In order to accelerate the reaction, temperature controlled environment was created, so that hardening could occur at normal time. No such difference in time of hardening was recorded for epoxy fixators, which was independent of the ambient temperature.

Epoxy compound remained in doughy consistency for relatively longer period, so it was comparatively easy to handle. Acrylic fixators required more expertise and time for application; moreover, it hardened quickly, giving very less time for minor adjustments. The epoxy fixators were comparatively easy to construct and took less time than acrylic fixators; as the time for hardening was relatively more than the acrylic, there was enough time for application and moulding over the pin scaffold allowing minor adjustments even after bone fixation. In addition, different gauges of tubing/PVC pipes can be used as moulds for application of acrylic fixators, whereas, epoxy putty can be hand moulded to various diameters depending upon the patients size for different ranges of weight.

The weight of the fixator is an important factor, which could influence the animals comfort and tolerance towards the fixator. An ideal fixator should be light in weight and strong. For the fixators having light weight components, the diameter and strength of the fixator can be increased without much increase in weight. Methylacrylates are lighter in weight than stainless steel fixators of comparable diameter (Lewis *et al*., 1998; Julie *et al*., 2007). Both acrylic and epoxy are lighter than metal fixators. Among the acrylic and epoxy used in the present study, the acrylic was significantly lighter in weight which was an advantage over epoxy material.

The cost of the fixation device sometimes dictates the selection of fixation technique, especially in animal patients. The acrylic fixator has been reported to be cheaper than metal fixators (Lewis *et al*., 1998; Julie *et al*., 2007). On an average, an acrylic fixator can be applied to an animal at a cost of ` 412.00 and epoxy fixator at ` 240.00, both of which are economical than commonly used KE ESF. The epoxy fixators were found more economical (about half the cost) than acrylic fixators. Hence, on the basis of ease of application and the cost of the fixator construct, the epoxy has an advantage over acrylic material.

The technique of applying ESF using acrylic/epoxy as connecting bar is easy, requires least instrumentation, materials required for fixator construction are readily available and is cost effective. Hence, this can be practiced in any remote place at the animal owner's door step with minimal training and facilities.

Part 2: *In vitro* biomechanical testing of different designs of acrylic and epoxy-pin external skeletal fixation systems

Biomechanics is defined as mechanics applied to biology (Smith, 1985). The forces applied in mechanical study cannot mimic the complex forces to which the bones are subjected to in the living system. These are pure forces, whereas in biological system, a force never acts alone but a combination of forces act. Biomechanics is a subspecialty of mechanical engineering focusing on the effects of forces on biological systems and materials used to enhance the biological system. These biomechanical testing do provide us with the information of stability of structures under various forces and their expected behaviour under them (Palmer *et al*., 1992; Radasch, 1999; White *et al*., 2003). In addition, we can compare various structures and thus help to facilitate decision making for clinical situations.

The pin diameter, length, number, plane of placement and material of fixator components are the major factors which can affect the mechanical characteristics of an external skeletal fixator. In the present study the diameter and length of pins used was kept constant. The size and number of pins used in external fixators depend on the size of patient and bone (Marcellin-Little, 1999).

Number of fixation pins in the proximal and distal bone fragments influences the fixators' stiffness and affects the distribution of the physiologic loads among pins. Increasing the number of pins distributes the force among the pins and increases the stiffness of the overall construct (David and Nirmal, 2007). The greater the number of fixation pins per fragment, the more effective is the device in stabilizing the fracture and maintain pin-bone interface integrity (Palmer *et al*., 1991; Bouvy *et al*., 1993). The pins should span the whole length of the segment (Anderson and St. Jean, 1996). In the present study, the strength of 3 pin support per segment were found significantly higher than the fixators with 2 pin support per segment under compression. The fixators with 3 support points per segment were 1.26 times stiffer than 2 point support per segment. The higher stiffness and modulus of the 3 pin support design may be due to its spanning the whole length of the segment and also due to more number of pins. This is in accordance with the previous reports in which it was found that 3 point fixation per bone segment was found more stable and stronger than 2 point fixation (Chao *et al*., 1979).

In 2 point support designs, the 8 (crossed) pin constructs were 1.14 times stiffer than 4 pin constructs under compression. A more marked difference was seen with 3 point support designs; where 12 pin constructs showed 1.34 times increase in stiffness than 6 pin constructs. This indicates that crossing the pins provides significantly higher stiffness and strength to the construct. There was a marked increase in the strength of the constructs with the increase in the complexity of designs. The uniplanar design was significantly weaker in axial compression than the other three designs namely multiplanar design-I, multiplanar design-II and circular design. As far as stress was concerned, the circular design was bearing significantly more stress in axial compression than the other three designs. Similar findings have been reported in earlier studies where the stiffness of the fixator increased with the complexity of design of fixators (Johnson and DeCamp, 1999; White *et al.*, 2003). For 2 support point designs, circular, multiplanar-II, multiplanar-I designs were more than 1.24, 1.11 and 1.08 times stiffer, respectively than the uniplanar design. A similar pattern was seen in 3 point support design, but the difference in stiffness was more. Here circular design was more than 1.42 times stiffer than uniplanar design. Multiplanar-I and multiplanar-II designs were about 1.30 times stiffer than uniplanar design.

There was no difference between the type of materials used i.e., acrylic or epoxy; however, a significant difference was seen between the type of designs. The multiplanar and circular designs were strongest in terms of stress bearing, stiffness and elastic modulus in axial compression. Thus, only the design was significantly affecting the strength of fixator, but connecting materials i.e. acrylic and epoxy had similar effect.

The mean ± SE value of stiffness (N/mm) of fixators under compression was 4189.24 ± 117.59, and was more than 2 times than that under bending (2060.28 ± 115.47). Bending forces result in the generation of maximum tensile forces on the convex surface of the bent subject and maximum compressive forces on the concave side. Thus a couple of forces act under bending, which might have resulted in lower stiffness. In addition, the gap present between the segments must have weakened the construct under bending. Under compression, an axial force is applied, which is applied only in one direction; when the load is applied in axial direction the gap present in between the segments keeps on reducing and finally the two segments join at certain point, which might result in increased stiffness of fixators under compression.

Similar to compression, in bending also there was a marked increase in the stiffness of the constructs with the increase in the complexity of the designs. The circular designs were markedly strong under bending forces. It was 2.28 times stiffer than the uniplanar design. The multiplanar designs were 1.6 times stronger than uniplanar design which was the weakest of all the other designs.

Similar to compression and bending, there was a marked increase in the stiffness of the constructs with the increase in the complexity of the designs under torsion tests. The uniplanar design was significantly weaker than the other three designs, multiplanar design-I, multiplanar design-II and circular design. Similar findings have been reported in earlier studies where the stiffness of the fixator increased with the complexity of the design of fixators (Johnson and DeCamp, 1999; White *et al.*, 2003).

Under torsion, circular design was the strongest, with about 18 times stiffer than uniplanar design. The multiplanar designs-II and I were 6 times and 3 times stiffer, respectively, than the uniplanar design.

A significant difference in torsional stiffness was recorded between multiplanar design -II and multiplanar design-I. Under torsional force, multiplanar design-II was about 2 times stiffer than multiplanar design-I. This implies that multiplanar design-II provides double rotational stability than multiplanar design-I. Thus by joining the connecting bars/side bars, the torsional stiffness increases markedly. Lauer *et al.* (2000) have reported that articulations/diagonals result in additional strength, without increasing stress at pin-bone interface. The articulation formed between side bars might have resulted in enhanced torsional stability. This can be very useful clinically, as without increasing pin number and pin insertion sites, more stable configuration can be achieved. Additional soft tissue trauma and morbidity associated can be avoided by utilizing the articulated design.

Epoxy has greater modulus of elasticity than acrylic and was suggested to be stiffer with same frame geometry (Roe and Keo, 1997). In the present study, however, there was no significant difference in the strength and stiffness between the acrylic and epoxy fixators. These differences could be due to the differences in the acrylic or epoxy materials used and also due to the differences in the techniques of their application. It can be suggested that the acrylic and epoxy materials used in the study can provide stable fixation and adequate strength required for an external skeletal fixator for use in dogs.

Circular designs were the strongest under all the three forces tested, but the construction requires comparatively more technical expertise. Moreover, acrylic circular fixator was very difficult to construct, as ring formation with corrugated pipes is cumbersome. Nevertheless, multiplanar design-II was comparatively easier to construct than the circular, provided sufficient stability under compression, bending and torsional forces is achieved. Further, it was stronger than multiplanar design-I, especially against rotational force. Taking these facts into consideration, multiplanar-II design was chosen for clinical evaluation.

Part 3: Clinical evaluation of acrylic and epoxy external skeletal fixation systems in fracture treatment

Preoperative observations

External skeletal fixation has the advantages of both internal and external fixation techniques. It allows cleaning and dressing of wound in open fractures, and it also provides stable fixation in unstable fractures. With minimal disturbance at the fracture site, this technique allows biological osteosynthesis. External skeletal fixation is generally preferred in open fractures to provide stable fixation and allow wound drainage and dressing (Johnson, 1999; Ozsoy and Altunatmaz, 2003). In the present study, 20 cases of zsimple (closed) and 7 cases of compound (open) fractures were treated using acrylic and epoxy-pin ESF.

In the present study, the number of males was relatively more than females. This was probably because males are generally more active and aggressive than their female counterparts, leading to trauma and fracture. In addition, there is a preferential keeping of male dogs by the owners, which could have also contributed to their more number. Aithal *et al*. (1999) and Kumar, (2007) have also reported a higher number of fractures in male dogs than females. However, an equal distribution of cases among males and females has also been reported (Hill, 1977; Denny, 1988).

Among different breeds, maximum cases presented were from mongrels. In addition Labrador, Spitz and German shepherd were also presented. Thilagar and Balasubramanium (1988) have reported a high number of fractures in Non-Descript dogs, followed by Pomeranian, German shepherd, Doberman, Labrador and Terrier. Whereas Balagopalan *et al*. (1995) have reported majority of cases in German shepherd, followed by Doberman, non-descript and Pomeranian. Kumar, (2007) have reported the higher incidence of fractures in Spitz and non-descript dogs. The number of cases from a particular breed depends on the breed population of that particular area. There is a large population of non-descript /mixed breed dogs in this locality, which may be the reason for more number of mongrels presented.

Non-descript dogs, are mostly let loose to roam around and hence are more prone to get injured (Aithal *et al*., 1999).

Road traffic accident (RTA) is reported to be the major cause of fracture among animals (Braden *et al*., 1995; Aithal and Singh, 1999, Harasen, 2003). In the present study, fall from the height was the major cause of long bone fracture along with RTA. Keeping pet dogs of a particular breed in a particular location is a major factor which affects the cause of trauma. The dogs generally run to chase some other animals like cats or monkeys, leading to fall or jump from height resulting in fracture.

Intraoperative observations

Three basic principles are considered when ESF is used (1) preoperative planning (2) application of the ESF, and (3) long term management. A deficiency in any one of these can lead to complications and an unsatisfactory clinical outcome (Rudd and Whitehair, 1992).

In the present study, all surgeries were performed under general anaesthesia. The limb involved was shaved, thoroughly cleaned and scrubbed. Surgical technique used for application of pins is an important factor affecting longevity of ESF (Anderson and St Jean, 1996). By standard surgical techniques the morbidity of the patient can be reduced. In the present study, all surgeries were performed by the same group of experienced surgeons to minimize variations and complications.

In fracture treatment with open approach, manipulations during the operation can cause additional trauma and blood supply will be damaged, causing a delay in wound healing (Dudley *et al.,* 1997; Lauer *et al.,* 2000). In the present study fractures were reduced with closed or semi open technique to minimize the soft tissue trauma, preserve vascular supply and adjacent supportive soft tissues; this technique limits iatrogenic tissue trauma, necrosis, and surgical infection due to overzealous manipulations and prolonged open procedures (Ozsoy and Altunatmaz, 2003). During surgery, priority was given to establish anatomical structure and protecting vascularization of the bone rather than to its reconstruction. This kind of an approach is the basis of biological osteosynthesis (Aron *et al.,* 1995; Johnson *et al.,* 1998; Palmer, 1999). Only in a few old cases with severe overriding of fragments, additional incision was made to facilitate fracture reduction.

Technique of pin insertion is very important as it may affect postoperative morbidity and complications. Bone necrosis is attributed to high temperatures attained during pin insertion, and mechanical properties of bone are reported to be irreversibly altered at temperatures greater than 50° C. Moroni *et al*. (1998) tested three different drill speeds in bone (hand drilling, 300 rpm, and 700 rpm) and found that drilling at 300 rpm resulted in significantly lower temperatures. However, in all the three drilling methods, the temperature required to thermally necrose osteoblasts was 55°C. High speed drilling has been shown to produce heat and thermal necrosis, whereas very low speed leads to wobbling and pin loosening (Egger *et al.*, 1986; Gumbs *et al.*, 1988; Clary and Roe, 1995;1996). In the present study, the pins were inserted using a low speed (200 rpm) electric drill. While passing pins with drill, continuous dropping of cold sterile normal saline solution with povidone iodine was done in order to minimize the possible thermal necrosis due to heat production. This technique was found satisfactory as complications of pin infection and loosening recorded were negligible.

Use of small diameter pins is increasing with the growing popularity of ring fixators and hybrid fixators. In dogs and cats, 1-1.6 mm K-wires were used most commonly (Ferriti, 1991; Kumar *et al.*, 2011). Thin pins are always bilateral, because they must be fixed under tension to provide stability between the fracture and frame. They carry the advantage of creating smaller defects in soft tissue and bone; however, as they are bilateral, care must be taken while passing pins through the skin and soft tissues as there are chances of neuro-vascular bundles to get entrapped and cause complications (Behrens, 1989). This was achieved in this study by introducing the pin by hand through the soft tissues up to the level of bone (most vessels and nerves were gently pushed aside by this method). A gap of 10-20 mm was kept between fixator side bars and skin to allow expected soft tissue swellings, facilitate pin tract care and cleaning (Lewis *et al*., 2001), which was found adequate in most of the cases.

Position of the bone within the fixator frame is also an important factor which can affect its stability. Fleming *et al.* (1989) observed greater axial stiffness but decreased torsional stiffness when bone was kept in an eccentric position with respect to the fixator. In the present study, in most of the cases, the bones were kept at the centre. In ESF, pins placed in the fracture fragments are generally connected to steel connecting bars through clamps or to the metallic rings through the fixation bolts (Van-EE and Geasling, 1992). Mouldable acrylics and epoxy putty have also been used to connect the transfixation pins (Ohashi *et al*., 1983; Tomlinson and Constantinescu, 1991; Ross and Matthiesen, 1993). This free-form type of fixation has the advantage that pin direction need not be influenced by the connecting bar location and the position of the fixator can be adjusted with respect to the limb.

The total time to apply fixator was almost equal in both acrylic and epoxy fixators. In acrylic fixators, application time was more but hardening time was less; whereas for epoxy fixators, application time was less and hardening time was more. The more time required for applying fixator in acrylic group was due to the extra time required to fix the corrugated pipe with the pins, their moulding, filling, sealing of pipe and then bending of pins. For epoxy fixator, a thorough mixing of two components i.e., resin and hardener was very important. These two components were to be mixed till a uniform colour of dough was attained which took about 1-2 min. The time required for hardening in case of acrylic was significantly less than epoxy, indicating that acrylic is relatively fast curing compound, which may be one of the reasons for high temperature attained during the process. In epoxy fixator, although the time required for applying fixator was less than that of acrylic, but the time for hardening was significantly longer than acrylic fixators. Hence the total time required for fixator application was similar for both acrylic and epoxy fixators.

There were certain disadvantages associated with application of acrylic fixators. First, the toxic fumes were produced while mixing acrylic powder with liquid, as also reported by others (Anderson, 1988). Secondly, while pouring the acrylic inside the pipe, there was leakage from the sites of pin insertion which made the field dirty and wet. Thirdly, the exothermic curing reaction resulted in generation of heat. Martinez *et al*. (1997) have suggested keeping a distance of at least 10 mm between the acrylic bars and skin to prevent tissue necrosis due to heat production. In the present study, a gap of about 10-20 mm was kept for the expected swelling due to inflammation without any complication.

The polymerization is an exothermic reaction, which reaches very high temperature. Thermal necrosis of sheep skin occurred with temperatures of 55°C applied for 1 min (Fraser, 1967). Thermal necrosis in rabbit bone occurred at 55°C or more, applied for 1 min (Fraser, 1967). Irreversible biomechanical changes occurred in a dog bone when it was heated to 50°C (Bonfield and Li, 1968). In order to prevent heat conduction from side bars to pins and then to the animal tissues, it was advised to pack ice in between the acrylic filled pipe columns and the skin, or alternatively to pour cold water on the skin to prevent possible thermal necrosis. It was reported that the temperature may reach about 50-55^{o}c, which is sufficient to cause thermal necrosis of biological tissues (Martinez *et al*., 1997). To prevent damage by this heat, in the present study, crushed ice was packed in between the skin and fixator frame and ice cold water was poured. Though this made the field dirty and the procedure cumbersome, it was found effective in minimizing the possible tissue necrosis. None of the animals showed any sign of tissue necrosis or excessive osteolysis/bone necrosis along the pin tracts.

Postoperative observations

Wound healing: The use of ESF avoids the need to place implants in an infected wound and keeps the wound accessible for drainage and daily dressing (Ness, 2006). In the present study open wounds healed within 15 days in all the 7 cases of open fractures without any complication. Cleaning and dressing of wounds was done with 1% povidone iodine. This indicates that free form of ESF using acrylic or epoxy, not only provides stable fixation of bone fragments, but also allow early soft tissue and wound healing. Ness (2006) reviewed 10 cases of dogs to assess the use of ESF with open wound management for treatment of unstable open or infected fractures, and concluded that open management of wounds with ESF, even when bone was exposed, proved to be an effective technique.

Status of the fixation device: The position of transosseous pins remained the same throughout the healing period. There was no pin bending or breakage during the postoperative period, till the fixator was removed. This shows that the pins provided stable fixation. Also, there was no breakage or change in the position of side bars (except for two cases) till the fracture healed and fixator was removed. This clearly indicate that the K-wires of 1.5 mm diameter and 15-20 mm diameter connecting bars made of acrylic or epoxy are strong enough to carry the weight of the animal and can be effectively used for the construction of ESF frame to provide rigid fixation of the fracture. Two cases of pin loosening were recorded; in one case, which was reported on day 5; the pin loosening occurred due to filling defect of the acrylic column in the PVC pipe. In the second case pin loosening was observed on day 45 radiograph, though its cause could not affect the fixation, which remained stable till fracture healed.

Pin tract sepsis: Loosening and infection are the two most common complications of external skeletal fixation. (Matthews *et al.,* 1984; Harari, 1992; Marcellin-Little, 1999). In the present study, pin tract sepsis was not a major complication. Pin tract sepsis occurs due to infection and necrosis of soft and osseous tissues (Green, 1989). In the majority of cases, the pin tracts remained dry indicating that proper technique was followed during the pin insertion and the acrylic/epoxy-pin fixators provided stable fixation of bone fragments. Mild to moderate discharge was observed in some cases, from most proximal pin tracts and in some cases also from the distal pins. Pin tract sepsis mostly seen in proximal pins may be due to the presence of more soft tissues, and more stress exerted on proximal pins during weight bearing. By regular cleaning, dressing and antibiotic coverage, the pin tract sepsis reduced gradually and subsequently it subsided without affecting the fixation adversely.

Gait analysis: The primary aim of fracture treatment is to achieve the fastest possible healing and enable the patient to function normally by allowing early walking (Aron, 1998; Shahar, 2000). In the present study the animals were observed postoperatively after 3 days for the analysis of gait pattern and weight bearing. Movement is a dynamic process and is best described in terms of observations made over time, rather than by observations of singular discrete events (Decamp *et al*., 1993). All the animals were observed during standing, walking and running for grading of weight bearing at all levels, at different time intervals.

Subjective scoring systems may be useful in clinical and research evaluation of gait, where obtaining and maintaining a force plate cannot be afforded (Quinn *et al*., 2007). Scores were made on the fact that a dog with a lesion causing severe sharp constant pain will carry the limb and keep the weight off (score 1), a comparatively less sharp pain will make slight weight bearing (score 2), a dull pain will make moderate weight bearing (score 3), and full weight bearing is observed in functional recovery from lesion (score 4). The more the score, the less will be the lameness in that particular animal.

Weight bearing was least in the immediate postoperative period in the animals of all the groups. Lameness in these animals was attributed to pain associated with fracture and fracture fixation.Overall, the standing score, walking score and running score, all increased gradually during the follow up period. Gradual increase in weight bearing indicates reduction in pain and a steady increase in the stability between the fracture fragments. As fracture healing proceeds, weight bearing improves (Ozsoy and Altunatmaz, 2003). The scores showed no difference when analyzed on the basis of fixator applied (acrylic or epoxy), bone involved (R/U or tibia), sex and type of wound (open or closed). This suggests that both fixators provided almost equal stability at the fracture site, irrespective of bone fractured, sex and type of fracture.

The standing scores remained the highest from the beginning till the end of observation period, followed by walking and running scores. Ground reaction force (GRF) is the opposite force exerted on the limbs when it is on the ground. GRF positively correlate with velocity and negatively correlate with the stance time (Roush and McLaughlin, 1994; McLaughlin and Roush, 1994). Stance time (duration that the foot is in contact with the ground) is more in standing, less in walking and least at running. More stance time (at walk) implies less GRF, this explains more gait scores were recorded at walking. Consequently, at running, the stance time was less thus maximum GRF was generated and less weight bearing was seen. Velocity (displacement per unit time) is also highest at running, thus generating maximum GRF; thereby least scores were recorded at running.

The age of the animal had a profound effect on the weight bearing. Young animals (< 2 years) showed better gait scores while standing, walking and running throughout the observation period. This may be attributed to the fact that young animals recorded faster rate of fracture healing and hence, showed better weight bearing than their old aged counterparts.

On the basis of their body weight, dogs of different groups showed similar gait scores while standing and walking. When observed at running, animals with more weight showed significantly lower scores. This may be due to the fact that most of the light weight animals were younger and heavy weight ones were older with slower rate of metabolism and fracture healing. In addition, the heavy weight animals due to their weight might get larger ground reaction force (Voss *et al.,* 2010), thus may feel more pain, thereby showing lower scores at running.

On the basis of degree of trauma (slight/moderate/severe), standing scores were similar in all groups. But standing scores and running scores were significantly lower in animals with severe trauma. This may be due to more soft tissue trauma and thus more pain associated with it in severely traumatized patients (Vogelsang and Laubenthal, 2008). This further suggests that the degree of soft tissue injury will also affect the degree of weight bearing and hence fracture healing.

On the basis of time since injury, the standing and walking scores were similar in various groups during the observation period. Whereas, running scores were lower in animals which were presented late for treatment. This indicates that delay in treatment may affect the functional recovery of the limb.

Antibiotic sensitivity test

In general *Staphylococcus* is the most commonly isolated microorganism from compound fractures, which could be due to its normal inhabitation on the animals' skin and the environment (Harari, 1992; Carneiro *et al.,* 2001; Kumar *et al.,* 2011).

Cefotaxim plus Sulbactum was administered to all the patients in the present study. Sulbactum is penicillinase enzyme inhibitor. Penicillinase is an enzyme which acts on the beta-lactam ring of the penicillin group of antibiotic and destroys it and is generally produced by penicillin resistant bacteria. In the present study, ampicillin-sulbactum combination came out to be the most effective antibiotic for which about 60 % of the samples were sensitive. Hirsh and Smith (1978) and Hunt *et al*. (1980) have recommended the use of penicillinase resistant penicillin.

Haemato-biochemical observations

In the present study no significant changes were recorded from the base values in the haematoloical parameters. Haemoglobin and PCV did not show any variation from the base values and were within the normal physiological limits throughout the observation period. Calcium and phosphorus were also within the normal levels at different intervals. The 2: 1 ratio of Ca: P was maintained throughout the observation period. This shows that the ESF used was least traumatic and hence, no significant changes in haemato-biochemical parameters were recorded.

Alkaline phosphatase (ALP) activity is one of the markers of bone formation. Increased ALP levels is associated with either skeletal or hepatobiliary diseases (Leroux and Perry, 1972). The values of ALP were within normal physiological limit but remained towards higher side in all the patients. This might be due to the fact that animals were presented in traumatized stage with increased ALP level. No further increase in ALP level was recorded during the postoperative period. Overall, the values remained within the normal physiological limit.

Radiographic observations

Although the epoxy-pin external fixator components were radio-opaque (which is a disadvantage as compared to acrylic) they did not interfere with radiographic evaluation of the fracture site in most dogs because, where possible, were the connecting bars were positioned away from the fracture site. The cranio-caudal radiographs allowed better visualization of fracture site than the medio-lateral radiographs. Nevertheless, acrylic is radiolucent on radiograph and is an advantage in clinical situation as compared to epoxy and stainless steel fixators (Lewis *et al*., 1998).

Fracture reduction and alignment was satisfactory to very good in postoperative radiographs in the majority of cases. In few cases, slight over riding of fracture fragments was seen which was mainly due to closed fracture reduction.

In most cases, none of the pins was broken (except for one case) throughout the observation period, indicating that the pins were of adequate diameter and the fixation was strong enough to bear the weight. Post-traumatic osteomyelitis is one of the most serious complications after open fractures (Soontornvipart *et al*., 2003). None of the animals of this study showed osteomyelitis. Osteolysis was also not seen in most of the animals, except in one where osteolysis was seen, that too in one pin tract only, suggesting stable pin bone interface. Incidentally, this animal was brought late for fixator removal.

In fractures of the long bones (radius and ulna or the tibia), a closed approach i.e., the use of external skeletal fixation (ESF) can be very useful as a biologic fracture repair, or bridging osteosynthesis will occur. Biological fracture healing will minimally disturb the fracture milieu; leaving the fracture’s blood clot, with all its osteoinductive components, and the blood supply to the surrounding bony and soft tissue, undisturbed (Harasen, 2002).

Preoperative and post operative radiographs were taken at regular intervals. The callus formation started as early as 15 days in some cases. Johnson *et al*. (1996) described a technique for closed reduction and application of a type-II ESF to communited fractures of radius and tibia in 23 dogs and found that mean time between surgery and development of bridging callus was 11.4 weeks and mean time between surgery and fixator removal was 14.7 weeks. Generally fracture healing occurs in about 3-12 weeks by application of ESF (Ozsoy and Altunatmaz, 2003). In the present study, healing occurred within 4-8 weeks with a mean time of 48.85 ± 2.56 days. Nevertheless, early uncomplicated healing observed in most cases suggest that when anatomical alignment is achieved healing can take place in a short time without the need for perfect positioning of the fragments (Ozsoy and Altunatmaz, 2003). Early healing may also be attributed to un-tensioned pins used in this free form of fixation, which allowed controlled micro motion at the fracture site, leading to early callus formation. This was supported by the fact that unlike in conventional ESF, where normally fracture heals by endosteal callus formation (Harari *et al.,* 1996), in the present study fractures generally healed by periosteal callus formation. Johnson *et al.* (1989) and Harari *et al.* (1996) have reported that fractures treated with external fixators healed with endosteal callus rather than periosteal callus, whereas, Ozsoy and Altunatmaz (2003) have reported fracture healing with the formation of a large callus (both periosteal and endosteal callus).

There was no significant effect of factors like fixator type (acrylic or epoxy), bone involved, sex, weight of the animal, cause of injury, time since injury, type of wound or degree of trauma on the fracture healing. But age of the animal had a significant effect on the fracture healing. The animals in the age group of 0-6 months took significantly ($P<0.05$) less time for fracture healing than animals in the age group of 1-2 year and above 2 year. The rate of fracture healing was comparatively faster in young animals, which may be due to more growth hormne and higher metabolic rate (Ekeland *et al*., 1982; Bak and Andreassen, 1991). The age-related decrease in fracture repair may be due to decrease in growth hormone secretion (Bak, and Andreassen, 1991). This shows that free form of ESF used in the present study provides stable fixation. Both acrylic and epoxy are equally effective in terms of stability and resulted in uncomplicated fracture healing.

Functional recovery

The aim of the treatment is to produce anatomical unity between the fractured bone and functioning of the extremity (Piermattei and Flo, 1997; Aron, 1998; Shahar, 2000). External fixation has advantages such as causing minimal damage to the injured region, maintaining bone length, minimizing the atrophy forming in the bone and soft tissues, allowing complete weight-bearing on the healing bone and keeping soft tissue trauma at the fracture line at the lowest (Johnson and Decamp, 1999; Egger, 1998; Lewis *et al.*, 2001).

In the present study, 92.59 % of the animals showed good to very good functional recovery after removal of fixator. This may be due to early weight bearing on the affected limb after the surgical fixation which might have avoided the possible complications such as bone and muscle atrophy, thereby allowing early return to function of the limb. This shows that the ESF using acrylic and epoxy as connecting material are strong enough and successful for treatment of fracture of long bones.

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SUMMARY AND CONCLUSIONS

External skeletal fixation (ESF) is a method of immobilization of an injured part using percutaneous pins that are connected outside the body to form a rigid frame or scaffold. Pins placed in the fracture fragments may be connected with moldable polymers rather than clamps and steel connecting bars. This free-form type of fixation has the advantage that pin direction need not be influenced by the connecting bar location and pin diameter need not be influenced by the clamp size.

The present study was planned with the objectives to design and develop different techniques of external skeletal fixation using acrylic and epoxy as external fixator components, to study the comparative *in vitro* biomechanical properties of acrylic and epoxy external skeletal fixation systems and to evaluate a suitable design of acrylic and epoxy-pin external skeletal fixators in the treatment of long bone fractures in dogs.

In part-I of the study, the technique of fixator construction was standardized. Fixator constructs were prepared using ultra high density polyethylene (UHDPE) rods of 20 mm diameter and 7 cm length of each segment. 1.5 mm diameter K-wires were passed at two or three points both in proximal and distal segments. Pins were passed in the same line, parallel to each other in uniplanar designs and were crossed in multiplanar-I, multiplanar-II and circular designs at 90^o angle. A gap of 5 mm (to simulate the unstable fracture condition) was kept in between the two segments of UHDPE rods. Side bars were constructed at a uniform distance of 20 mm from the plastic rod. Total length and diameter of fixators was 14.5 cm and 10 cm, respectively, including the connecting bars. For acrylic fixators PVC pipes of 20 mm diameter were connected to the pins in the same plane by piercing through and through. Acrylic powder was mixed with liquid in pre-cooled glass beaker in the ratio of 2:1 and acrylic in liquid state was poured into the pipes to form the side bars and rings. In epoxy fixators the pins in the same plane were bent and joined using adhesive tape to form a temporary scaffold. Extra wire pieces were used to construct rings. Then, the epoxy monomer was mixed with polymer to make a dough. The epoxy in dough stage was applied along the scaffold keeping the pins within to form the side bars and rings.

Thus different designs of acrylic and epoxy fixators were constructed viz. uniplanar (one side bar in each side), multiplanar design-I (2 bars on each side), multiplanar design-II (side bars in each side connected at proximal and distal ends) and circular (2 rings one each in proximal and distal ends). The technical easiness, time required for fixator application, hardening time, weight and cost of the fixator were recorded for different designs of acrylic and epoxy-pin ESF systems.

In the second part of the study, biomechanical testing of the fixator constructs was done. Compression testing was done on two designs of fixators i.e., 2-point fixation per segment and 3-point fixation per segment. The fixator constructs were mounted on Servohydraulic Universal Testing Machine (UTM) and axial load was applied @ 3mm/sec. The load deflection graphs were plotted and stress (N/mm^2), strain, modulus of elasticity (N/mm^2) and stiffness (N/mm) of fixator constructs were calculated. Bending and torsion tests were done only on 3-point fixation per segment constructs. In bending test, the fixator constructs were mounted on the UTM in the form of Simply Supported Beam and a Uniformly Distributed Load (UDL) was applied @ 3 mm/sec, till failure. Bending moment (KN-mm), modulus of elasticity (N/mm^2) and stiffness (N/mm) were calculated. For torsion testing, the fixator constructs were mounted on the Torsion Testing Machine (TTM) with the help of the coupling device. One end of the construct was fixed and the other end was rotated @ 20 degree per minute. The torque (Nm) and the degree required to fail the constructs were recorded. Shear stress (N/mm^2), shear strain and stiffness (N/mm^2) were calculated.

On the basis of part I and II of the study, based on the ease of construction and biomechanical properties, multiplanar design-II was selected for use in clinical cases. Clinical examination was done on the cases selected, which were randomly divided into two groups (A and E). Animals of group A were treated with acrylic ESF, and group E were treated with epoxy ESF. Anamnesis regarding the species, breed, age and sex of the animal, cause of fracture, time since fracture and bone involved were recorded in each case. The fractured bone was subjected to radiographic examination in orthogonal views. Fracture reduction and fixation was done by closed or semi-open method under general anaesthesia. The pins were inserted through bone using a low speed (200 rpm) electric drill with continuous dropping of cold sterile normal saline solution. The pins were crossed with each other at an angle of 70^o-90^o. In general, 1.5 mm K-wires were used in radius/ulna and tibia/fibula, whereas in some cases of transarticular fixation, 1.2 mm K-wires were passed through metacarpals and metatarsals. A hybrid of multiplanar-II and uniplanar designs was used in the cases where fracture was near the joint. For acrylic fixator, after passing the pins, 20 mm diameter corrugated mouldable PVC pipes of desired length were connected to the pins to construct the side bars, the acrylic was then poured into the pipes, open ends of the pipes were joined with the help of adhesive tape. Crushed ice was kept in between the fixator columns and skin, and the acrylic columns were then allowed to harden. For epoxy fixator, after passing the pins, the pins were bent towards the facture site; the bent pins were then joined with the help of adhesive tape to form a temporary scaffold. Using additional pin pieces, the two side bars on each side were joined at the proximal and distal ends. The epoxy hardener and resin were then mixed thoroughly and epoxy putty was then hand moulded and applied along the scaffold. The epoxy fixator so formed was then allowed to harden.

During fixation of fracture, the time required for fracture reduction, time required for passing pins, construction of side bars and hardening was recorded. The number of pins passed through the bone fragments, the diameter and the direction of pins used, and the distance between the skin and side bars was recorded in each case. The diameter of the acrylic/epoxy columns was noted. The technical easiness/difficulties during the application of fixators and the degree of fracture stability achieved at the time of fixation were recorded.

Meloxicam @ 0.2 mg/kg and Taximax @ 25 mg/kg were administered IM on the day of surgery, subsequently oral administration was advised for 3-5 days. Regular cleaning and dressing of the wound was done with 1% povidone iodine. Wound healing, status of the fixation device, pin tract sepsis was recorded and subjective gait analysis was done from day 3 to 45 postoperatively, at regular intervals. Samples were collected from the wound site and pin-skin interfaces at different intervals and antibiotic sensitivity test was performed. In addition, haemoglobin (Hb-g/L), packed cell volume (PCV-%), alkaline phosphatase (Units/L), calcium (mmol/L) and phosphorus (mmol/L) were estimated at regular intervals. Orthogonal radiographs were made immediately after the application of fixator and at regular 15 day intervals, till fracture healing. After the radiographic healing, the fixator was removed by cutting the pins with a pin cutter.

Acrylic fixators were radiolucent and relatively light weight. But acrylic fixators were relatively costly, difficult to apply and produced more heat and fumes during application. Epoxy fixators were more economical, easy to apply because of their doughy state, produced less heat and no fumes, but were relatively heavy and radiopaque. Hardening time for acrylic was dependent on environmental temperature with an average of 11 min; whereas, epoxy putty hardened in about 22 min and the hardening was independent of environmental temperature. Circular fixators needed maximum time and technical expertise for preparation, followed by multiplanar designs, whereas uniplanar designs took least time. Acrylic fixators needed relatively more time for construction and more technical expertise than epoxy fixators.

Fixators with 3-point fixation per segment were stronger than fixators with 2-point fixation per segment in terms of higher stress bearing capacity and higher modulus of elasticity. Multiplanar designs (Multiplanar design-I & II and circular) were stiffer than uniplanar design. As the number of pins increased, the strength of fixator increased under compression. Circular design was the strongest in axial compression, bending and torsion. Uniplanar designs were the weakest under all forces. Multiplanar-I and II designs came at par under compression and bending. However, multiplanar-II design, provided more rotational stability than multiplanar-I design. Biomechanically, among acrylic and epoxy fixators, there was no significant difference.

Acrylic and epoxy-pin fixators were used for the treatment of 20 closed fractures and 7 open fractures in dogs (18 males, 9 females). In acrylic group, 7 R/U and 5 tibial fractures were treated, whereas, in epoxy group 10 R/U and 5 tibial fractures were treated. There were 12 mixed breed dogs, 4 Spitz, 4 Labrador, 3 German shepherd, 2 Rottweiler, 1 Great Dane and 1 Doberman; 6 dogs were having body weight up to 10 kg, 13 dogs were in the range of 10-20 kg and 8 dogs were having weight more than 20 kg. The most common causes of fractures were falls from height (13) or vehicular injury (11). Fourteen cases were presented within 5 days of injury, 7 cases in between 5 and 15 days, and 6 dogs in more than 15 days of fracture/injury. All surgeries were done under general anaesthesia. 1.5 mm K- wires were passed at angle 50^o-80^o from cranio-medial to caudo-lateral and caudo-medial to to cranio-lateral directions in R/U and T/F. A gap of about 1-2 cm was left between skin and side bars of fixators. The total time required for application (applying fixator and hardening) was 56-59 min for both fixators.

Very good to good fracture fragment reduction was obtained in 29.63 % and 51.85 % cases, respectively. The status of pins and side bars of fixators was maintained throughout the postoperative period with minimal pin tract sepsis. Open wounds healed within 15 days. Ampicillin + sulbactum was the most effective antibiotic seen in sensitivity test. No significant changes were observed in Hb, PCV, Ca, P and ALP levels at various time intervals.

During the postoperative period, the mean gait scores increased gradually in all the groups. Standing scores were highest, followed by walking and running, at any particular time interval. Early presented cases with less soft tissue trauma showed better gait scores. Young animals with less body weight showed better gait scores. No significant difference was seen in fracture healing between acrylic and epoxy fixators, although younger animals showed relatively early healing. The mean ± SE time required for fracture healing in all groups was 48.85 ± 2.56 days. Both acrylic and epoxy fixators provided stable fracture fixation in dogs with good to very good functional recovery in 92.59 % cases.

From the results of this study, the following conclusions were drawn :

1. Different designs of external skeletal fixators like uniplanar, multiplanar and circular can be developed using epoxy-putty or dental acrylic; however, epoxy fixation is relatively easy.

2. Epoxy external skeletal fixation is better than acrylic fixation in terms of easy handling and manoeuvrability, no heat and fume production, and economy; whereas acrylic fixators are light weight and radiolucent.

3. Circular designs of external skeletal fixators are strongest under compression, bending and torsion, followed by multiplanar and uniplanar designs. Multiplanar design-II provides double the rotational stability than multiplanar design-I.

4. No significant difference between acrylic and epoxy-pin fixation systems, in terms of biomechanical properties, and fracture fixation and healing.
5. Both acrylic and epoxy-pin fixators provide stable fixation of fractures in dogs with early healing and functional recovery.
6. The technique of acrylic or epoxy-pin external skeletal fixation is easy, economical, needs minimal instrumentation and hence can be practised by a field veterinarian in any remote place.

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Mini Abstract

The present study was undertaken in three parts. In the first part the development of different designs of acrylic and epoxy-pin ESF systems was done, using 20 mm diameter UHDPE pipes and 1.5 mm K-wires. Different designs of acrylic and epoxy fixators i.e., uniplanar, multiplanar-I, multiplanar-II and circular were prepared. Data regarding the time for construction, hardening, weight and cost of fixators were recorded. In the second part of study, *in vitro* biomechanical testing was performed on the fixator-constructs under compression, bending and torsion loads. Based on the results of part-I and II, multiplanar design-II was used in the third part to evaluate the acrylic and epoxy-pin ESF systems for treatment of long bone fractures in dogs. Surgical fixation of the fractured radius-ulna or tibia was done under general anaesthesia with closed or semiopen method. K-wires of 1.2-1.5 mm diameter were used. In acrylic fixators, PVC pipes of 20 mm diameter were fixed to the pins and acrylic was poured into the pipes with sealed ends. Crushed ice was kept between the skin and fixators to reduce thermal necrosis. In epoxy fixators, pins in the same plane were bent and joined with adhesive tape to form a temporary scaffold. Epoxy putty was applied along the pins. The fixators were then allowed to harden. Postoperatively, animals were observed till fracture healing. Data regarding wound healing, pin tract sepsis and status of fixation device was recorded. Gait analysis was done 3 days after surgery to 45th day. Hb, PCV, Ca, P and ALP were estimated at regular intervals. Radiographs were taken regularly, till fractures healed.

Acrylic fixators were radiolucent, light weight, but were relatively more costly, difficult to apply and produced more heat and fumes during application. Epoxy fixators were more economical, easy to apply and produced low heat, but relatively heavy and radiopaque. Biomechanically, among acrylic and epoxy type fixators, there was no significant difference. As the number of pins increased, the strength of the fixator increased. Circular design was the strongest in axial compression, bending and torsion. Multiplanar-I and II designs were at par under compression and bending; however, under torsion multiplanar design -II was 2 times stronger than design-I. Uniplanar designs were the weakest under all forces. During the postoperative period, the mean gait scores increased gradually in all the groups. Early presented cases, with less soft tissue trauma showed better gait scores. Young animals with less body weight showed better gait scores. No significant difference in fracture healing between acrylic and epoxy fixators was observed although younger animals showed relatively early healing. Both acrylic and epoxy fixators provided stable fracture fixation in dogs with good to very good functional recovery in 92.59 % cases. The technique of application of acrylic or epoxy-pin ESF provides stable fixation of long bone fractures and is also cost effective, easy and can be practiced at any remote place with minimal facilities.

लघु सारांश

प्रस्तुत अध्ययन तीन भागों में किया गया। प्रथम चरण में एक्रिलिक एवं इपोक्सि पिन इएसएफ के विभिन्न अभिकल्पों में 20 एमएम वर्तुल के यूएचडीपीई नाली तथा 1.5 के तारों से विकसित किया गया तथा निर्माण, कठोर काल, वजन तथा मूल्य आँका गया। द्वितीय चरण में पात्र जैव यान्त्रिकी आंकलन, दबाव, मोड़ना तथा मरोड़ के बल मूल्यांकित किये गये। अध्ययन के प्रथम एवं द्वितीय चरण के आधार पर तृतीय चरण में एक्रिलिक एवं इपेक्सि पिन इएसएफ पद्धति की जाँच कुत्तों के उरोस्थि एवं जंघास्थि के अस्थिभंग में अवलोकित किया गया। शल्यक्रिया के पश्चात घाव का भरना, पिन मार्ग संक्रमण तथा युक्ति की स्थिति, प्रेक्षक अस्थिभंग जुड़ने तक किया गया। साथ ही हिमोग्लोबिन, पीसीवी, कैल्शियम, फास्मोरस, एएलपी तथा क्षरूपिकी भी की गई।

एक्रिलिक पारदर्शी, हलके, महंगे, लगाने में कठिन, अत्याधिक उष्मा जनन वाले जबकि इपोक्सि किफायती, लगाने में सरल, कम उष्मा जनन, वजन में भारी परन्तु क्षरूपिकी में अपारदर्शी। जैवयान्त्रिकि में दोनों एक से ही पाये गये। जिनकी संख्या बढ़ाने पर एसएएफ संराकविरण बढ़ा। वर्तुलाकार अभिकल्प सीधे दबाव, मोड़ एवं मरोड़न में प्रतिरोधी पाया गया। बहुदिशीय अभिकल्प–2 मरोड़ प्रतिरोधी पाया गया। एक्रिलिक एवं इपोकिस दोनों से ही अस्थिभंग जुड़ना एक सा–ही पाया गया। शल्यक्रिया के बाद कुल चाल विश्लेषांक में वृद्धि परनतु तुरन्त लाये गये न्यूनतम क्षति के साथ लाये गये पशुओं चाल अंक अच्छा पाया गया। युवा पशुओं में फ्रेक्चर शीघ्र जुड़ा। दोनों ही युक्तियों से स्थिर स्थायीकरा प्रदत्त हुआ तथा क्रियाशील सुधार 92.59 प्रतिशत पशुरूग्णों में पाया गया। एक्रिलिक अथवा इपोक्सिपित इएसएफ तकनीक से लम्बी अस्थियो में न केवल स्थिर स्थायीकरण हुआ परन्तु यह सरल, किफायती तथा दुर्गम स्थानों पर कम से कम सुविधाओं भी लगाया जा सकता है।

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Table 1: *The mean ± SE values of weight (g) of filling material and fixator.*

Group	Factor	N	Weight of filling material (g)	Weight of fixator (g)
Filling material	Acrylic	28	132.50 ± 10.20	262.50 ± 14.93
	Epoxy	28	405.35 ± 29.18	472.85 ± 29.83
Model	Uniplanar	14	126.42 ± 19.90^{a}	206.42 ± 14.47^{a}
	Multiplanar design-I	14	237.85 ± 31.18^{ab}	332.85 ± 24.27^{b}
	Multiplanar design-II	14	308.57 ± 44.95^{bc}	408.57 ± 36.67^{b}
	Circular	14	402.85 ± 56.31^{c}	522.85 ± 42.59^{c}
Interaction (Filling material* Model)	Acrylic uniplanar	7	55.71 ± 2.02^{a}	155.57 ± 2.02^{a}
	Acrylic multiplanar design-I	7	125.71 ± 2.02^{b}	245.71 ± 2.02^{b}
	Acrylic multiplanar design-II	7	147.14 ± 3.59^{c}	277.14 ± 3.59^{c}
	Acrylic circular	7	201.42 ± 5.94^{d}	371.42 ± 5.94^{d}
	Epoxy uniplanar	7	194.14 ± 6.80^{d}	257.14 ± 6.80^{b}
	Epoxy multiplanar design-I	7	350.00 ± 4.36^{e}	420.00 ± 4.36^{e}
	Epoxy multiplanar design-II	7	47.00 ± 7.55^{f}	540.00 ± 7.55^{f}
	Epoxy circular	7	604.28 ± 13.60^{g}	674.28 ± 13.60^{g}
	Overall	56	268.92 ± 23.93	367.67 ± 23.93

Means with different superscripts in the same column differ significantly.

Table 1(a): *ANOVA of the weight (g) of filling material and fixator.*

Variable	**Parameters**		**Sum of Square**	**df**	**Mean Square**	**F**
Fixator type	Weight of the fixator (g)	Between groups	619501.79	1	619501.79	39.71**
		Within groups	842496.43	54	15601.79	
		Total	1461998.21	55		
	Weight of the filling material (g)	Between groups	1042314.29	1	1042314.29	77.87**
		Within groups	722821.43	54	13385.58	
		Total	1765135.71	55		
Design	Weight of the fixator (g)	Between groups	741533.93	3	247177.98	17.84**
		Within groups	720464.29	52	13855.08	
		Total	1461998.21	55		
	Weight of the filling material (g)	Between groups	570921.43	3	190307.14	8.29**
		Within groups	1194214.29	52	22965.66	
		Total	1765135.71	55		
Interaction	Weight of the fixator (g)	Between groups	1446712.50	7	206673.21	648.99**
		Within groups	15285.71	48	318.45	
		Total	1461998.21	55		
	Weight of the filling material (g)	Between groups	1749850.00	7	249978.57	784.98**
		Within groups	15285.71	48	318.45	
		Total	1765135.71	55		
		Within groups	9284.76	48	193.43	
		Total	1052691.97	55		

**(P<0.01); *(P<0.05)

Table 2: *The mean ± SE values of cost (Rs) of filling material and fixator.*

Group	Factor	N	Cost of filling material (g)	Cost of fixator (g)
Filling material	Acrylic	28	254.40 ± 19.59^{a}	411.90 ± 26.80^{a}
	Epoxy	28	83.09 ± 5.98^{b}	240.59 ± 12.77^{b}
Model	Uniplanar	14	73.69 ± 9.43^{a}	163. 69 ± 9.43^{a}
	Multiplanar design-I	14	156.56 ± 23.59^{b}	336.56 ± 23.59^{b}
	Multiplanar design-II	14	189.43 ± 26.03^{bc}	369.43 ± 26.03^{bc}
	Circular	14	255.31± 36.88^{c}	435.31± 36.88^{c}
Interaction (Filling material* Model)	Acrylic uniplanar	7	106.97 ± 3.87^{c}	196.97 ± 3.87^{b}
	Acrylic multiplanar design-I	7	241.37 ± 3.87^{e}	421.37 ± 3.87^{f}
	Acrylic multiplanar design-II	7	282.51 ± 6.90^{f}	462.51 ± 6.90^{g}
	Acrylic circular	7	386.74 ± 11.41^{g}	566.74 ± 11.41^{h}
	Epoxy uniplanar	7	40.41 ± 1.39^{a}	130.41 ± 1.39^{a}
	Epoxy Multiplanar design-I	7	71.75 ± 0.89^{b}	251.75 ± 0.89^{c}
	Epoxy multiplanar design-II	7	96.35 ± 1.54^{c}	276.35 ± 1.54^{d}
	Epoxy circular	7	123.87 ± 2.78^{d}	303.87 ± 2.78^{e}
	Overall	56	168.74 ± 15.37	367.67 ± 18.48

Means with different superscripts in the same column differ significantly.

Table 2(a): *ANOVA of cost (Rs.) of filling material and fixator.*

Variable	**Parameters**		**Sum of Square**	**df**	**Mean Square**	**F**
Fixator type	Cost of the filling material (Rs)	Between groups	410820.23	1	410820.23	69.92**
		Within groups	317279.99	54	5875.56	
		Total	728100.22	55		
	Total cost of the fixator	Between groups	410820.23	1	410820.23	34.56**
		Within groups	641871.74	54	11886.51	
		Total	1052691.97	55		
Design	Cost of the filling material (Rs)	Between groups	239469.26	3	79823.09	8.49**
		Within groups	488630.95	52	9396.75	
		Total	728100.22	55		
	Total cost of the fixator	Between groups	564061.01	3	188020.34	20.01**
		Within groups	488630.95	52	9396.75	
		Total	1052691.97	55		
Interaction	Cost of the filling material (Rs)	Between groups	718815.46	7	102687.92	530.87**
		Within groups	9284.76	48	193.43	
		Total	728100.22	55		
	Total cost of the fixator	Between groups	1043407.21	7	149058.17	770.60**
		Within groups	9284.76	48	193.43	
		Total	1052691.97	55		

**(P<0.01); *(P<0.05)

Table 3: *The mean ± SE values of time required (min.) to apply fixator in vitro.*

Group	Factor	N	Time (min.)
Filling material	Acrylic	28	20.32 ± 1.33^{a}
	Epoxy	28	13.60 ± 0.87^{b}
Model	Uniplanar	14	8.78 ± 0.64^{a}
	Multiplanar design-I	14	16.35± 0.92^{b}
	Multiplanar design-II	14	19.07 ± 0.99^{b}
	Circular	14	23.64 ± 1.66^{c}
Interaction (Filling material* Model)	Acrylic uniplanar	7	10.71 ± 0.56^{b}
	Acrylic multiplanar design-I	7	19.28 ± 0.60^{e}
	Acrylic multiplanar design-II	7	22.14 ± 0.91^{f}
	Acrylic circular	7	29.14 ± 1.12^{g}
	Epoxy uniplanar	7	6.85 ± 0.508^{a}
	Epoxy multiplanar design-I	7	13.42 ± 0.72^{c}
	Epoxy multiplanar design-II	7	16.00 ± 0.57^{d}
	Epoxy circular	7	18.14 ± 0.85^{de}
	Overall	56	16.96 ± 0.90

Means with different superscripts in the same column differ significantly.

Table 3(a): *ANOVA of time required (min.) to apply fixator in vitro.*

Variable	**Parameters**		**Sum of Square**	**df**	**Mean Square**	**F**
Fixator type	Time required to apply fixator (min.)	Between groups	631.143	1	631.143	17.762**
		Within groups	1918.786	54	35.533	
		Total	2549.929	55	542.738	
Design	Time required to apply fixator (min.)	Between groups	1628.214	3	17.725	30.619**
		Within groups	921.714	52		
		Total	2549.929	55		
Interaction (Filling material* Model)	Time required to apply fixator (min.)	Between groups	2355.929	7	336.561	83.273**
		Within groups	194.000	48	4.042	
		Total	2549.929	55		

**(P<0.01); *(P<0.05)

Table 4: *The mean ± SE values of stress, strain, stiffness and modulus of elasticity in fixators with 2 support points per segment under compression.*

Group	Factor	N	Stress (N/mm^2)	Strain	Stiffness (N/mm)	Modulus of elasticity
Number of pins	4	8	41.43 ± 1.19	0.0345 ± 0.0017	3001.01 ±114.9^{a}	1215.18 ± 48.69^{a}
	8	24	44.02 ± 0.63	0.0322 ± 0.0008	3434.18 ± 99.01^{b}	1388.18 ± 41.12^{b}
	Acrylic	16	41.79 ± 0.61^{b}	0.0323 ± 0.009	3246.27 ± 93.71	1309.11 ± 38.27
	Epoxy	16	44.96 ± 0.85^{a}	0.0333 ± 0.0012	3405.5 ± 143.85	1380.75 ± 59.61
Model	Uniplanar	8	41.43 ± 1.19	0.0345 ± 0.0017	3001.01 ± 114.9^{a}	1215.18 ± 48.69^{a}
	Multiplanar design-I	8	43.62 ± 1.00	0.0334 ± 0.0012	3246.93 ± 133.14^{a}	1318.63 ± 55.77^{ab}
	Multiplanar design-II	8	43.33 ± 0.80	0.0329 ± 0.0017	3333.17 ± 174.98^{ab}	1343.18 ± 71.93^{ab}
	Circular	8	45.11 ± 1.44	0.0304 ± 0.0013	3722.45 ± 173.07^{b}	1502.72 ± 74.33^{b}
Interaction (Filling material* Model)	Acrylic uniplanar	4	39.72 ± 0.81	0.0333 ± 0.0026	2977.11 ± 220.68	1214.3 ± 89.07
	Acrylic multiplanar design-I	4	41.66 ± 1.11	0.0329 ± 0.0014	3163.76 ± 92.43	1270.01 ± 41.51
	Acrylic multiplanar design-II					
	Acrylic circular	4	43.65 ± 1.37	0.0309 ± 0.0013	3553.69 ± 157.35	1420.9 ± 68.85
	Epoxy uniplanar	4	43.14 ± 2.00	0.0357 ± 0.0024	3024.91 ± 111.93	1216.06 ± 55.94
	Epoxy multiplanar design-I	4	45.58 ± 0.91	0.0338 ± 0.0021	3330.1 ± 263.75	1367.25 ± 105.91
	Epoxy multiplanar design-II	4	44.54 ± 0.98	0.0337 ± 0.0029	3375.81 ± 326.53	1355.14 ± 130.33
	Epoxy circular	4	46.56 ± 2.52	0.0299 ± 0.0024	3891.2 ± 309.9	1584.55 ± 128.76
	Overall	32	43.37 ± 0.59	0.0328 ± 0.0008	3325.89 ± 85.65	1344.93 ± 35.43

Means with different superscripts in the same column differ significantly.

***Table 4(a):** ANOVA of stress, strain, stiffness and modulus of elasticity in fixators with 2-support points under per segment compression.*

Variable	Parameters		Sum of Square	df	Mean Square	F
Number of pins	Stress (N/mm^2)	Between groups	40.31	1	40.31	4.02
		Within groups	301.16	30	10.04	
		Total	341.47	31		
	Strain	Between groups	0.000031	1	0.0000312	1.73
		Within groups	0.000541	30	0.0000180	
		Total	0.000573	31		
	Stiffness (N/mm)	Between groups	1125835.15	1	1125835.15	5.49*
		Within groups	6150839.14	30	205027.97	
		Total	7276674.29	31		
	Modulus of elasticity (N/mm^2)	Between groups	179566.81	1	179566.81	5.05*
		Within groups	1065955.45	30	35531.85	
		Total	1245522.26	31		
Filling material	Stress (N/mm^2)	Between groups	80.20	1	80.20	9.21**
		Within groups	261.27	30	8.71	
		Total	341.47	31		
	Strain	Between groups	0.000008	1	0.000008	0.42
		Within groups	0.000565	30	0.000019	
		Total	0.00057	31		
	Stiffness (N/mm)	Between groups	202834.43	1	202834.43	0.86
		Within groups	7073839.86	30	235794.66	
		Total	7276674.29	31		
	Modulus of elasticity (N/mm^2)	Between groups	41057.03	1	41057.03	1.02
		Within groups	1204465.24	30	40148.84	
		Total	1245522.26	31		
Model	Stress (N/mm^2)	Between groups	54.84	3	18.28	1.79
		Within groups	286.64	28	10.24	
		Total	341.47	31		
	Strain	Between groups	0.00007	3	0.0000242	1.36
		Within groups	0.00050	28	0.0000179	
		Total	0.00057	31		
	Stiffness (N/mm)	Between groups	2152729.40	3	717576.47	3.92*
		Within groups	5123944.89	28	182998.03	
		Total	7276674.29	31		
	Modulus of elasticity (N/mm^2)	Between groups	339424.21	3	113141.40	3.50*
		Within groups	906098.06	28	32360.64	
		Total	1245522.26	31		
Interaction (Filling material* Model)	Stress (N/mm^2)	Between groups	137.56	7	19.65	2.31
		Within groups	203.91	24	8.50	
		Total	341.47	31		
	Strain	Between groups	0.000093	7	0.000013	0.67
		Within groups	0.000479	24	0.000020	
		Total	0.000573	31		
	Stiffness (N/mm)	Between groups	2454998.89	7	350714.13	1.75
		Within groups	4821675.40	24	200903.14	
		Total	7276674.29	31		
	Modulus of elasticity (N/mm^2)	Between groups	413048.91	7	59006.99	1.70
		Within groups	832473.36	24	34686.39	
		Total	1245522.26	31		

**(P<0.01); *(P<0.05)

Table 5: *The mean ± SE values of stress, strain, stiffness and modulus of elasticity in fixators with 3 support points under compression.*

Group	Factor	N	Stress (N/mm^2)	Strain	Stiffness (N/mm)	Modulus of Elasticity
Number of Pins	6	8	48.5 ± 0.70^{a}	0.0362 ± 0.0016^{a}	3339.97 ± 137.35^{a}	1354.81 ± 55.67^{a}
	12	24	55.28 ± 0.85^{b}	0.0308 ± 0.0007^{b}	4472.33 ± 94.85^{b}	1810.54 ± 38.17^{b}
Filling material	Acrylic	16	53.07 ± 1.08	0.0333 ± 0.0011	4038.74 ± 171.37	1621.33 ± 65.92
	Epoxy	16	54.09 ± 1.30	0.0309 ± 0.0009	4339.75 ± 157.35	1771.88 ± 64.53
Model	Uniplanar	8	48.5 ± 0.7^{a}	0.0362 ± 0.0016^{a}	3339.97 ± 137.35^{a}	1354.81 ± 55.67^{a}
	Multiplanar design-I	8	52.95 ± 0.9^{b}	0.0304 ± 0.0010^{b}	4314.17 ± 137.29^{b}	1753.56 ± 57.28^{b}
	Multiplanar design-II	8	54.1 ± 1.46^{b}	0.0308 ± 0.0011^{b}	4352.26 ± 156.36^{b}	1768.09 ± 67.96^{b}
	Circular	8	58.78 ± 1.17^{c}	0.0311 ± 0.0014^{b}	4750.57 ± 169.38^{b}	1909.96 ± 65.76^{b}
Interaction (Filling material* Model)	Acrylic uniplanar	4	47.85 ± 1.10^{a}	0.0377 ± 0.0024^{b}	3170.71 ± 182.72^{a}	1283.08 ± 72.33^{a}
	Acrylic multiplanar design-I	4	53.41 ± 0.92^{bc}	0.0319 ± 0.0017^{ab}	4191.72 ± 174.54^{b}	1684.55 ± 62.13^{b}
	Acrylic multiplanar design-II	4	53.79 ± 1.79^{bc}	0.0319 ± 0.0012^{ab}	4226.71 ± 256.02^{b}	1697.6 ± 104.24^{b}
	Acrylic circular	4	57.21 ± 1.79^{cd}	0.0319 ± 0.0027^{ab}	4565.8 ± 307.64^{bc}	1820.08 ± 111.28^{bc}
	Epoxy uniplanar	4	49.14 ± 0.88^{ab}	0.0348 ± 0.0021^{ab}	3509.24 ± 188.53^{a}	1426.53 ± 76.18^{a}
	Epoxy multiplanar design-I	4	52.48 ± 1.68^{abc}	0.0289 ± 0.0006^{a}	4436.61 ± 217.95^{bc}	1822.57 ± 90.98^{bc}
	Epoxy multiplanar design-II	4	54.4 ± 2.59^{c}	0.0298 ± 0.0019^{a}	4477.8 ± 195.02^{bc}	1838.59 ± 85.87^{bc}
	Epoxy circular	4	60.35 ± 1.25^{d}	0.0303 ± 0.0012^{a}	4935.33 ± 128.38^{c}	1999.85 ± 49.14^{c}
	Overall	32	53.58 ± 0.84	0.0321 ± 0.0008	4189.24 ± 117.59	1696.61 ± 47.35

Means with different superscripts in the same column differ significantly.

Table 5(a): *ANOVA of stress, strain, stiffness and modulus of elasticity in fixators with 3-support points per segment under compression.*

Variable	**Parameters**		**Sum of Square**	**df**	**Mean Square**	**F**
Number of pins	Stress (N/mm^2)	Between groups	275.85	1	275.85	19.60**
		Within groups	422.25	30	14.07	
		Total	698.10	31		
	Strain	Between groups	0.000179	1	0.0001787	14.01**
		Within groups	0.000383	30	0.0000128	
		Total	0.000561	31		
	Stiffness (N/mm)	Between groups	7693385.97	1	7693385.97	38.32**
		Within groups	6022398.81	30	200746.63	
		Total	13715784.78	31		
	Modulus of elasticity (N/mm^2)	Between groups	1246152.64	1	1246152.64	38.24**
		Within groups	977618.75	30	32587.29	
		Total	2223771.39	31		
Filling material	Stress (N/mm^2)	Between groups	8.42	1	8.42	0.37
		Within groups	689.67	30	22.99	
		Total	698.10	31		
	Strain	Between groups	0.000047	1	0.000047	2.75
		Within groups	0.000514	30	0.000017	
		Total	0.00056	31		
	Stiffness (N/mm)	Between groups	724851.93	1	724851.93	1.67
		Within groups	12990932.85	30	433031.10	
		Total	13715784.78	31		
	Modulus of elasticity (N/mm^2)	Between groups	181335.40	1	181335.40	2.66
		Within groups	2042435.99	30	68081.20	
		Total	2223771.39	31		
Model	Stress (N/mm^2)	Between groups	428.62	3	142.87	14.85**
		Within groups	269.48	28	9.62	
		Total	698.10	31		
	Strain	Between groups	0.00018	3	0.0000602	4.43*
		Within groups	0.00038	28	0.0000136	
		Total	0.00056	31		
	Stiffness (N/mm)	Between groups	8628192.47	3	2876064.16	15.83**
		Within groups	5087592.30	28	181699.73	
		Total	13715784.78	31		
	Modulus of elasticity (N/mm^2)	Between groups	1365618.87	3	455206.29	14.85**
		Within groups	858152.52	28	30648.30	
		Total	2223771.39	31		
Interaction (Filling material* Model)	Stress (N/mm^2)	Between groups	454.08	7	64.87	6.38**
		Within groups	244.01	24	10.17	
		Total	698.10	31		
	Strain	Between groups	0.000230	7	0.000033	2.39
		Within groups	0.000331	24	0.000014	
		Total	0.000561	31		
	Stiffness (N/mm)	Between groups	9376530.26	7	1339504.32	7.41**
		Within groups	4339254.52	24	180802.27	
		Total	13715784.78	31		
	Modulus of elasticity (N/mm^2)	Between groups	1549259.31	7	221322.76	7.87**
		Within groups	674512.08	24	28104.67	
		Total	2223771.39	31		

**(P<0.01); *(P<0.05)

Table 6 : *The mean ± SE values of stress, strain, stiffness and modulus of elasticity in fixators with 2- and 3- support points per segment under compression.*

Variable	**Group**	**N**	**Stress (N/mm^2)**	**Strain**	**Stiffness (N/mm)**	**Modulus of elasticity (N/mm^2)**
Support Points	2	32	43.37 ± 0.59^{a}	0.0328 ± 0.0043	3325.89 ± 85.65^{a}	1344.93 ± 35.43^{a}
	3	32	53.58 ± 0.84^{b}	0.0321 ± 0.0043	4189.24 ± 117.59^{b}	1696.61 ± 47.35^{b}

Means with different superscripts in the same column differ significantly.

Table 6(a) : *The mean ± SE values of stress, strain, stiffness and modulus of elasticity in fixators with 2- and 3- support points per segment under compression.*

Variable	**Parameters**		**Sum of Square**	**df**	**Mean Square**	**F**
Support points	Stress (N/mm^2)	Between groups	1666.75	1	1666.75	99.41**
		Within groups	1039.57	62	16.77	
		Total	2706.32	63		
	Strain	Between groups	0.000007	1	0.000007	0.36
		Within groups	0.001134	62	0.000018	
		Total	0.001140	63		
	Stiffness (N/mm)	Between groups	11930000.00	1	11930000.00	35.22**
		Within groups	20990000.00	62	338588.05	
		Total	32920000.00	63		
	Modulus of Elasticity (N/mm^2)	Between groups	1978814.56	1	1978814.56	35.36**
		Within groups	3469293.65	62	55956.35	
		Total	5448108.21	63		
		Within groups	3984456.72	60	66407.61	
		Total	5448108.21	63		

**(P<0.01); *(P<0.05)

Table 7: *The mean ± SE values of bending moment, stiffness and modulus of elasticity in fixators under bending.*

Variable	**Group**	**N**	**Bending moment (KN-mm)**	**Stiffness (N/mm)**	**Modulus of Elasticity (N/mm^{2})**
Filling material	Acrylic	16	11545 ± 88.77	2023.96 ± 166.68	240.34 ± 18.07
	Epoxy	16	11879 ± 86.25	2096.6 ± 164.79	247.25 ± 17.48
Model	Uniplanar	8	7642 ± 69.79^{a}	1281.37 ± 115.6^{a}	160.25 ± 14.63^{a}
	Multiplanar design I	8	11682 ± 60.68^{b}	2058.34 ± 128.93^{b}	244.97 ± 12.73^{b}
	Multiplanar design II	8	11779 ± 68.94^{b}	2103.72 ± 153.54^{b}	247.01 ± 14.46^{b}
	Circular	8	15744 ± 74.91^{c}	2797.69 ± 134.25^{c}	322.97 ± 15.36^{c}
Interaction	Acrylic uniplanar	4	6911.9 ± 76.86^{a}	1179.74 ± 122.74^{a}	144.94 ± 16.12^{a}
	Acrylic multiplanar design I	4	11779 ± 78.49^{b}	2048.07 ± 150.83^{b}	247.01 ± 16.46^{b}
	Acrylic multiplanar design II	4	11877 ± 90.63^{b}	2097.31 ± 223.72^{b}	249.05 ± 19.00^{b}
	Acrylic circular	4	15611 ± 100.57^{c}	2770.73 ± 205.83^{c}	320.38 ± 20.64^{c}
	Epoxy uniplanar	4	8372.2 ± 115.19^{a}	1383.01 ± 201.02^{a}	175.56 ± 24.15^{a}
	Epoxy multiplanar design I	4	11585 ± 104.70^{b}	2068.62 ± 234.00^{b}	242.92 ± 21.95^{b}
	Epoxy multiplanar design II	4	11682 ± 117.90^{b}	2110.13 ± 244.82^{b}	244.97 ± 24.72^{b}
	Epoxy circular	4	15877 ± 126.32^{c}	2824.65 ± 203.11^{c}	325.55 ± 25.90^{c}
Overall		32	11712 ± 60.95	2060.28 ± 115.47	243.8 ± 12.38

Means with different superscripts in the same column differ significantly.

Table 7(a): *ANOVA of bending moment, stiffness and modulus of elasticity in fixators under bending.*

Variable	**Parameters**		**Sum of Square**	**df**	**Mean Square**	**F**
Filling material	Bending moment (N-mm)	Between groups	8.93 X 10^{11}	1	8.93 X 10^{11}	0.07
		Within groups	3.68 X 10^{14}	30	1.23 X 10^{13}	
		Total	3.69 X 10^{14}	31		
	Shear modulus (N/mm^2)	Between groups	3.82 X 10^{2}	1	3.82 X 10^{2}	0.08
		Within groups	1.52 X 10^{5}	30	5.06 X 10^{3}	
		Total	1.52 X 10^{5}	31		
	Stiffness (N/mm)	Between groups	4.22 X 10^{4}	1	4.22 X 10^{4}	0.10
		Within groups	1.32 X 10^{7}	30	4.40 X 10^{5}	
		Total	1.32 X 10^{7}	31		
Model	Bending moment (N-mm)	Between groups	2.63 X 10^{14}	3	8.75 X 10^{13}	23.1**
		Within groups	1.06 X 10^{14}	28	3.78 X 10^{12}	
		Total	3.69 X 10^{14}	31		
	Shear modulus (N/mm^2)	Between groups	1.06 X 10^{5}	3	3.54 X 10^{4}	21.53**
		Within groups	4.60 X 10^{4}	28	1.64 X 10^{3}	
		Total	1.52 X 10^{5}	31		
	Stiffness (N/mm)	Between groups	9.22 X 10^{6}	3	3.07 X 10^{6}	21.46**
		Within groups	4.01 X 10^{6}	28	1.43 X 10^{5}	
		Total	1.32 X 10^{7}	31		
Interaction	Bending moment (N-mm)	Between groups	2.67 X 10^{14}	7	3.82 X 10^{13}	9.04**
		Within groups	1.01 X 10^{14}	24	4.22 X 10^{12}	
		Total	3.69 X 10^{14}	31		
	Shear modulus (N/mm^2)	Between groups	1.08 X 10^{5}	7	1.54 X 10^{4}	8.42**
		Within groups	4.40 X 10^{4}	24	1.83 X 10^{3}	
		Total	1.52 X 10^{5}	31		
	Stiffness (N/mm)	Between groups	9.31 X 10^{6}	7	1.33 X 10^{6}	8.14**
		Within groups	3.92 X 10^{6}	24	1.63 X 10^{5}	
		Total	1.32 X 10^{7}	31		

**($P<0.01$); *($P<0.05$)

Table 8: *The mean ± SE values of shear stress, shear modulus and stiffness in fixators under torsion.*

Variable	**Group**	**N**	**Shear stress (N/mm^2)**	**Shear modulus (N/mm^2)**	**Stiffness (Nm/deg)**
Filling material	Acrylic	16	79.06 ± 10.09	182.92 ± 44.54	0.33 ± 0.08
	Epoxy	16	80.73 ± 10.10	196.82 ± 49.45	0.35 ± 0.09
Model	Uniplanar	8	37.23 ± 2.72 ^{a}	27.03 ± 1.45 ^{a}	0.048 ± 0.003 ^{a}
	Multiplanar design I	8	55.23 ± 1.88 ^{b}	81.23 ± 1.10 ^{b}	0.145 ± 0.002 ^{b}
	Multiplanar design II	8	88.74 ± 2.47 ^{c}	162.23 ± 5.00 ^{c}	0.29 ± 0.009 ^{c}
	Circular	8	138.37 ± 3.21 ^{d}	489 ± 24.76 ^{d}	0.875 ± 0.044 ^{d}
Interaction	Acrylic uniplanar	4	35.72 ± 2.97 ^{a}	26.74 ± 1.80 ^{a}	0.048 ± 0.003 ^{a}
	Acrylic multiplanar design I	4	55.04 ± 2.68 ^{b}	81.1 ± 2.13 ^{a}	0.145 ± 0.004 ^{a}
	Acrylic multiplanar design II	4	88.4 ± 4.27 ^{c}	162.09 ± 9.14 ^{b}	0.29 ± 0.016 ^{b}
	Acrylic circular	4	137.09 ± 5.74 ^{d}	461.74 ± 43.96 ^{d}	0.827 ± 0.079 ^{c}
	Epoxy uniplanar	4	38.74 ± 4.91 ^{a}	27.32 ± 2.56 ^{a}	0.049 ± 0.005 ^{a}
	Epoxy multiplanar design I	4	55.43 ± 3.05 ^{b}	81.36 ± 1.06 ^{a}	0.146 ± 0.002 ^{a}
	Epoxy multiplanar design II	4	89.08 ± 3.18 ^{c}	162.36 ± 5.74 ^{b}	0.291 ± 0.010 ^{b}
	Epoxy circular	4	139.66 ± 3.73 ^{d}	516.26 ± 20.82 ^{c}	0.924 ± 0.037 ^{d}
Overall		32	79.89 ± 7.02	189.87 ± 32.76	0.34 ± 0.059

Means with different superscripts in the same column differ significantly.

Table 8(a): *ANOVA of shear stress, shear modulus and stiffness in fixators under torsion.*

Variable	Parameters		Sum of Square	df	Mean Square	F
Filling material	Shear stress (N/mm^2)	Between groups	22.11	1	22.11	0.01
		Within groups	48917.48	30	1630.58	
		Total	48939.59	31		
	Shear modulus (N/mm^2)	Between groups	1547.54	1	1547.54	0.04
		Within groups	1062888.76	30	35429.63	
		Total	1064436.30	31		
	Stiffness (Nm/deg)	Between groups	0.005	1	0.005	0.04
		Within groups	3.41	30	0.114	
		Total	3.41	31		
Model	Shear stress (N/mm^2)	Between groups	47410.62	3	15803.54	289.41**
		Within groups	1528.96	28	54.61	
		Total	48939.59	31		
	Shear modulus (N/mm^2)	Between groups	1028510.00	3	342836.67	267.20**
		Within groups	35926.30	28	1283.08	
		Total	1064436.30	31		
	Stiffness (Nm/deg)	Between groups	3.30	3	1.099	267.20**
		Within groups	0.12	28	0.004	
		Total	3.41	31		
Interaction	Shear stress (N/mm^2)	Between groups	47443.22	7	6777.60	108.71**
		Within groups	1496.36	24	62.35	
		Total	48939.59	31		
	Shear modulus (N/mm^2)	Between groups	1034454.58	7	147779.23	118.30**
		Within groups	29981.72	24	1249.24	
		Total	1064436.30	31		
	Stiffness (Nm/deg)	Between groups	3.31	7	0.474	118.30**
		Within groups	0.10	24	0.004	
		Total	3.41	31		

**(P<0.01); *(P<0.05)

Table 9 : *Mean ± SE of time required (min) for passing wires, applying fixator, hardening and total time of fixator application in acrylic and epoxy groups.*

Parameters (min)	**Acrylic (n=12)**	**Epoxy (n=15)**	**Overall mean (n=27)**
Time for passing pins	14.92 ± 1.00	15.20 ± 1.13	15.07 ± 0.75
Time for applying fixators	29.58 ± 2.26[a]	19.67 ± 1.42[b]	24.07 ± 1.58
Time for hardening	10.67 ± 0.41[a]	22.00 ± 0.52[b]	16.96 ± 1.15
Total time	59.17 ± 3.34	56.87 ± 2.28	57.89 ± 1.92

Means with different superscripts in the same row differ signfiicantly

Table 9(a): *ANOVA of time required for passing wires, applying fixator, hardening and total time of fixator application (min) in acrylic and epoxy group.*

Groups	**Source of variation**	**Sum of Square**	**df**	**Mean Square**	**F value**
Time for passing pins	Between groups	0.54	1	0.54	0.03
	Within groups	397.32	25	15.89	
	Total	397.85	26		
Time for applying fixators	Between groups	655.60	1	655.60	14.95*
	Within groups	1096.25	25	43.85	
	Total	1751.85	26		
Time for hardening	Between groups	856.30	1	856.30	272.13*
	Within groups	78.67	25	3.15	
	Total	934.96	26		
Total time	Between groups	35.27	1	35.27	0.34
	Within groups	2561.40	25	102.46	
	Total	2596.67	26		

**(P<0.01); *(P<0.05)

Table 10 : *Gait scores of animals in standing, walking and running at various days.*

Variable	Group	Day	N	Standing score	Walking score	Running score
Fixator type	Acrylic	3	12	2.08 ± 0.26	2.00 ± 0.17	1.17 ± 0.11
	Epoxy		15	2.33 ± 0.23	2.13 ± 0.19	1.20 ± 0.11
	Acrylic	7	12	2.75 ± 0.22	2.75 ± 0.18	1.75 ± 0.18
	Epoxy		15	2.67 ± 0.19	2.67 ± 0.16	1.60 ± 0.16
	Acrylic	15	12	3.08 ± 0.26	2.83 ± 0.11	2.08 ± 0.19
	Epoxy		15	3.00 ± 0.20	2.73 ± 0.21	2.13 ± 0.24
	Acrylic	30	12	3.58 ± 0.23	3.17 ± 0.17	2.58 ± 0.29
	Epoxy		15	3.40 ± 0.16	3.00 ± 0.22	2.53 ± 0.26
	Acrylic	45	12	3.75 ± 0.18	3.50 ± 0.19	2.92 ± 0.29
	Epoxy		15	3.67 ± 0.19	3.13 ± 0.17	2.53 ± 0.22
Age group	0-6 months	3	4	1.75 ± 0.48 ^{a}	2.25 ± 0.48 ^{b}	1.50 ± 0.29
	6- 12 months		11	2.73 ± 0.27 ^{b}	2.27 ± 0.14 ^{b}	1.27 ± 0.14
	1-2 year		6	2.33 ± 0.21 ^{ab}	2.33 ± 0.21 ^{b}	1.00 ± 0.00
	Above 2 years		6	1.50 ± 0.22 ^{a}	1.33 ± 0.21 ^{a}	1.00 ± 0.00
	0-6 months	7	4	3.00 ± 0.41 ^{b}	3.00 ± 0.00 ^{b}	2.25 ± 0.48
	6- 12 months		11	2.82 ± 0.18 ^{b}	2.82 ± 0.12 ^{b}	1.64 ± 0.15
	1-2 year		6	3.00 ± 0.00 ^{b}	3.00 ± 0.00 ^{b}	1.67 ± 0.21
	Above 2 years		6	2.00 ± 0.37 ^{a}	2.00 ± 0.37 ^{a}	1.33 ± 0.21
	0-6 months	15	4	3.25 ± 0.48	3.25 ± 0.25 ^{b}	2.50 ± 0.65
	6- 12 months		11	3.27 ± 0.19	2.82 ± 0.12 ^{ab}	2.27 ± 0.24
	1-2 year		6	3.00 ± 0.00	3.00 ± 0.00 ^{b}	2.00 ± 0.00
	Above 2 years		6	2.50 ± 0.50	2.17 ± 0.40 ^{a}	1.67 ± 0.33
	0-6 months	30	4	3.75 ± 0.25	3.25 ± 0.48	3.00 ± 0.71
	6- 12 months		11	3.64 ± 0.20	3.36 ± 0.15	2.64 ± 0.28
	1-2 year		6	3.67 ± 0.21	3.00 ± 0.00	2.67 ± 0.21
	Above 2 years		6	2.83 ± 0.31	2.50 ± 0.43	2.00 ± 0.45
	0-6 months	45	4	4.00 ± 0.00	3.75 ± 0.25 ^{b}	3.50 ± 0.50
	6- 12 months		11	3.82 ± 0.18	3.55 ± 0.21 ^{ab}	2.73 ± 0.27
	1-2 year		6	3.67 ± 0.33	2.83 ± 0.17 ^{a}	2.50 ± 0.34
	Above 2 years		6	3.33 ± 0.33	3.00 ± 0.26 ^{ab}	2.33 ± 0.33
Sex	Male	3	18	2.06 ± 0.21	2.06 ± 0.17	1.17 ± 0.09
	Female		9	2.56 ± 0.29	2.11 ± 0.20	1.22 ± 0.15
	Male	7	18	2.72 ± 0.19	2.61 ± 0.16	1.67 ± 0.16
	Female		9	2.67 ± 0.17	2.89 ± 0.11	1.67 ± 0.17

Table 10 : *Gait scores of animals in standing, walking and running at various days (Contd...).*

Variable	**Group**	**Day**	**N**	**Standing score**	**Walking score**	**Running score**
	Male	15	18	3.06 ± 0.17	2.78 ± 0.15	2.06 ± 0.19
	Female		9	3.00 ± 0.33	2.78 ± 0.22	2.22 ± 0.28
	Male	30	18	3.50 ± 0.15	3.00 ± 0.18	2.61 ± 0.23
	Female		9	3.44 ± 0.29	3.22 ± 0.22	2.44 ± 0.34
	Male	45	18	3.83 ± 0.12	3.22 ± 0.13	2.67 ± 0.21
	Female		9	3.44 ± 0.29	3.44 ± 0.29	2.78 ± 0.32
Treatment groups	Acrylic-Radius/Ulna	3	7	1.71 ± 0.36	1.86 ± 0.26	1.00 ± 0.00
	Acrylic-Tibia		5	2.60± 0.24	2.20 ± 0.20	1.40 ± 0.24
	Epoxy-Radius/Ulna		10	2.40 ± 0.34	2.30 ± 0.26	1.30 ± 0.15
	Epoxy-Tibia		5	2.20 ± 0.20	1.80 ± 0.20	1.00 ± 0.00
	Acrylic-Radius/Ulna	7	7	2.57 ± 0.30	2.71 ± 0.29	1.57 ± 0.20
	Acrylic-Tibia		5	3.00 ± 0.32	2.80 ± 0.20	2.00 ± 0.32
	Epoxy-Radius/Ulna		10	2.60 ± 0.27	2.70 ± 0.21	1.60 ± 0.22
	Epoxy-Tibia		5	2.80 ± 0.20	2.60 ± 0.24	1.60 ± 0.24
	Acrylic-Radius/Ulna	15	7	2.86 ± 0.40	2.86 ± 0.14	2.14 ± 0.26
	Acrylic-Tibia		5	3.40 ± 0.24	2.80 ± 0.20	2.00 ± 0.32
	Epoxy-Radius/Ulna		10	3.20 ± 0.20	2.90 ± 0.23	2.30 ± 0.33
	Epoxy-Tibia		5	2.60 ± 0.40	2.40 ± 0.40	1.80 ± 0.20
	Acrylic-Radius/Ulna	30	7	3.43 ± 0.37	3.14 ± 0.26	2.71 ± 0.42
	Acrylic-Tibia		5	3.80 ± 0.20	3.20 ± 0.20	2.40 ± 0.40
	Epoxy-Radius/Ulna		10	3.60 ± 0.16	3.10 ± 0.31	2.80 ± 0.33
	Epoxy-Tibia		5	3.00 ± 0.32	2.80 ± 0.20	2.00 ± 0.32
	Acrylic-Radius/Ulna	45	7	3.57 ± 0.30	3.43 ± 0.30	3.00 ± 0.44
	Acrylic-Tibia		5	4.00 ± 0.00	3.60 ± 0.24	2.80 ± 0.37
	Epoxy-Radius/Ulna		10	3.80 ± 0.20	3.30 ± 0.21	2.60 ± 0.31
	Epoxy-Tibia		5	3.40 ± 0.40	2.80 ± 0.20	2.40 ± 0.24
Weight groups	Up to 10 kg	3	6	1.67 ± 0.33	2.33 ± 0.33	1.33 ± 0.21
	10-20 Kg		13	2.23 ± 0.20	1.77 ± 0.12	1.08 ± 0.08
	Above 20 kg		8	2.63 ± 0.38	2.38 ± 0.26	1.25 ± 0.16
	Up to 10 kg	7	6	2.67 ± 0.33	3.00 ± 0.00	1.83 ± 0.40
	10-20 kg		13	2.77 ± 0.17	2.69 ± 0.17	1.77 ± 0.12
	Above 20 kg		8	2.63 ± 0.32	2.50 ± 0.27	1.38 ± 0.18
	Up to 10 kg	15	6	3.00 ± 0.37	3.17 ± 0.17	2.83 ± 0.48^{b}
	10-20 kg		13	3.15 ± 0.22	2.62 ± 0.21	1.92 ± 0.14^{a}
	Above 20 kg		8	2.88 ± 0.30	2.75 ± 0.16	1.88 ± 0.23^{a}

Table 10 : *Gait scores of animals in standing, walking and running at various days (Contd...).*

Variable	Group	Day	N	Standing score	Walking score	Running score
	Up to 10 kg	30	6	3.50 ± 0.34	3.33 ± 0.33	3.33 ± 0.49
	10-20 kg		13	3.62 ± 0.18	3.00 ± 0.23	2.23 ± 0.20
	Above 20 kg		8	3.25 ± 0.25	3.00 ± 0.19	2.50 ± 0.33
	Up to 10 kg	45	6	4.00 ± 0.00	3.83 ± 0.17	3.67 ± 0.33^{b}
	10-20 kg		13	3.62 ± 0.21	3.23 ± 0.20	2.54 ± 0.22^{a}
	Above 20 kg		8	3.63 ± 0.26	3.00 ± 0.19	2.25 ± 0.25^{a}
Cause of injury	Accident	3	11	2.45 ± 0.28	2.18 ± 0.18	1.36 ± 0.15
	Fall from height		13	2.08 ± 0.26	2.08 ± 0.21	1.08 ± 0.08
	Hit by stick		3	2.00 ± 0.00	1.67 ± 0.33	1.00 ± 0.00
	Accident	7	11	2.73 ± 0.24	2.55 ± 0.21	1.73 ± 0.19
	Fall from height		13	2.62 ± 0.21	2.77 ± 0.17	1.54 ± 0.18
	Hit by stick		3	3.00 ± 0.00	3.00 ± 0.00	2.00 ± 0.00
	Accident	15	11	3.09 ± 0.25	2.82 ± 0.18	2.09 ± 0.25
	Fall from height		13	3.00 ± 0.25	2.69 ± 0.21	2.15 ± 0.25
	Hit by stick		3	3.00 ± 0.00	3.00 ± 0.00	2.00 ± 0.00
	Accident	30	11	3.45 ± 0.21	3.09 ± 0.16	2.45 ± 0.28
	Fall from height		13	3.46 ± 0.22	3.08 ± 0.26	2.62 ± 0.31
	Hit by stick		3	3.67 ± 0.33	3.00 ± 0.00	2.67 ± 0.33
	Accident	45	11	3.73 ± 0.19	3.18 ± 0.18	2.45 ± 0.25
	Fall from height		13	3.85 ± 0.15	3.54 ± 0.18	3.08 ± 0.24
	Hit by stick		3	3.00 ± 0.58	2.67 ± 0.33	2.00 ± 0.58
Time since injury	Up to 5 days	3	14	2.07 ± 0.25	2.21 ± 0.19	1.14 ± 0.10
	5-15 days		7	2.14 ± 0.26	1.86 ± 0.26	1.29 ± 0.18
	Above 15 days		6	2.67 ± 0.42	2.00 ± 0.26	1.17 ± 0.17
	Up to 5 days	7	14	2.64 ± 0.20	2.64 ± 0.17	1.50 ± 0.17
	5-15 days		7	2.86 ± 0.34	2.71 ± 0.29	2.00 ± 0.22
	Above 15 days		6	2.67 ± 0.21	2.83 ± 0.17	1.67 ± 0.21
	Up to 5 days	15	14	3.14 ± 0.14	2.79 ± 0.19	2.36 ± 0.25
	5-15 days		7	3.00 ± 0.38	2.86 ± 0.14	2.00 ± 0.22
	Above 15 days		6	2.83 ± 0.48	2.67 ± 0.33	1.67 ± 0.21
	Up to 5 days	30	14	3.43 ± 0.17	3.14 ± 0.21	2.93 ± 0.25
	5-15 days		7	3.57 ± 0.30	3.00 ± 0.22	2.43 ± 0.37
	Above 15 days		6	3.50 ± 0.34	3.00 ± 0.37	1.83 ± 0.31
	Up to 5 days	45	14	4.00 ± 0.00^{b}	3.43 ± 0.14	3.00 ± 0.23
	5-15 days		7	3.43 ± 0.30^{a}	3.14 ± 0.26	2.43 ± 0.37
	Above 15 days		6	3.33 ± 0.42^{a}	3.17 ± 0.40	2.33 ± 0.33

Table 10 : *Gait scores of animals in standing, walking and running at various days (Contd...).*

Variable	Group	Day	N	Standing score	Walking score	Running score
Type of wound	Open	3	7	2.14 ± 0.40	2.14 ± 0.26	1.14 ± 0.14
	Closed		20	2.25 ± 0.19	2.05 ± 0.15	1.20 ± 0.09
	Open	7	7	2.43 ± 0.37	2.43 ± 0.30	1.29 ± 0.18
	Closed		20	2.80 ± 0.14	2.80 ± 0.12	1.80 ± 0.14
	Open	15	7	2.71 ± 0.36	2.57 ± 0.20	2.29 ± 0.42
	Closed		20	3.15 ± 0.17	2.85 ± 0.15	2.05 ± 0.15
	Open	30	7	3.14 ± 0.34	3.14 ± 0.26	2.71 ± 0.47
	Closed		20	3.60 ± 0.13	3.05 ± 0.17	2.50 ± 0.20
	Open	45	7	3.86 ± 0.14	3.43 ± 0.20	2.86 ± 0.34
	Closed		20	3.65 ± 0.17	3.25 ± 0.16	2.65 ± 0.21
Degree of trauma	Slight	3	20	2.35 ± 0.21	2.10 ± 0.16	1.25 ± 0.10
	Moderate		4	1.50 ± 0.29	2.00 ± 0.41	1.00 ± 0.00
	Severe		3	2.33 ± 0.33	2.00 ± 0.00	1.00 ± 0.00
	Slight	7	20	2.90 ± 0.14^{b}	2.85 ± 0.11	1.85 ± 0.13^{b}
	Moderate		4	2.00 ± 0.41^{a}	2.50 ± 0.50	1.25 ± 0.25^{ab}
	Severe		3	2.33 ± 0.33^{a}	2.50 ± 0.00	1.00 ± 0.00^{a}
	Slight	15	20	3.30 ± 0.13^{b}	2.90 ± 0.12	2.10 ± 0.16
	Moderate		4	2.25 ± 0.48^{a}	2.75 ± 0.25	2.50 ± 0.65
	Severe		3	2.33 ± 0.67^{a}	2.00 ± 0.58	1.67 ± 0.33
	Slight	30	20	3.70 ± 0.11^{b}	3.15 ± 0.17	2.65 ± 0.20
	Moderate		4	3.00 ± 0.58^{a}	3.00 ± 0.41	2.75 ± 0.75
	Severe		3	2.67 ± 0.33^{a}	2.67 ± 0.33	1.67 ± 0.33
	Slight	45	20	3.75 ± 0.14	3.35 ± 0.15	2.70 ± 0.21
	Moderate		4	3.75 ± 0.25	3.50 ± 0.29	3.25 ± 0.48
	Severe		3	3.33 ± 0.67	2.67 ± 0.33	2.00 ± 0.00
Bone involved	Radius/Ulna	3	17	2.12 ± 0.26	2.12 ± 0.19	1.18 ± 0.10
	Tibia		10	2.40 ± 0.16	2.00 ± 0.15	1.20 ± 0.13
	Radius/Ulna	7	17	2.59 ± 0.19	2.71 ± 0.17	1.59 ± 0.15
	Tibia		10	2.90 ± 0.18	2.70 ± 0.15	1.80 ± 0.20
	Radius/Ulna	15	17	3.06 ± 0.20	2.88 ± 0.15	2.24 ± 0.22
	Tibia		10	3.00 ± 0.26	2.60 ± 0.22	1.90 ± 0.18
	Radius/Ulna	30	17	3.53 ± 0.17	3.12 ± 0.21	2.76 ± 0.25
	Tibia		10	3.40 ± 0.22	3.00 ± 0.15	2.20 ± 0.25
	Radius/Ulna	45	17	3.71 ± 0.17	3.35 ± 0.17	2.76 ± 0.25
	Tibia		10	3.70 ± 0.21	3.20 ± 0.20	2.60 ± 0.22

Means with different superscripts in the same row differ significantly.

Table 11: *Mean ± SE values of haematobiochemical parameters in animals of different groups at various intervals.*

Parameters	Day	Acrylic-Radius/Ulna (n=7)	Acrylic-Tibia (n=5)	Epoxy-Radius/Ulna (n=10)	Epoxy-Tibia (n=5)	Overall (n=27)
Haemoglobin (g/L)	0	10.14 ± 0.51	9.68 ± 1.26	10.70 ± 0.30	10.00 ± 1.22	10.24 ± 0.35
	7	10.07 ± 0.73	10.00 ± 1.30	11.00 ± 0.47	9.90 ± 1.17	10.37 ± 0.40
	15	10.57 ± 0.54	10.30 ± 0.89	10.70 ± 0.30	9.70 ± 0.99	10.41 ± 0.29
	30	10.29 ± 0.58	10.30 ± 0.89	10.70 ± 0.31	10.40 ± 0.87	10.46 ± 0.28
	45	10.71 ± 0.47	10.40 ± 0.68	11.05 ± 0.28	10.80 ± 0.66	10.80 ± 0.23
Packed Cell Volume (%)	0	28.43 ± 3.05	34.40 ± 2.75	30.40 ± 2.43	33.20 ± 4.93	31.15 ± 1.55
	7	30.43 ± 2.05	35.80 ± 3.29	32.50 ± 1.38	34.40 ± 3.33	32.93 ± 1.12
	15	31.43 ± 1.77	34.60 ± 4.01	32.70 ± 1.40	34.60 ± 3.03	33.07 ± 1.10
	30	29.43 ± 1.93	33.40 ± 2.09	31.80 ± 1.53	34.20 ± 1.77	31.93 ± 0.92
	45	33.86 ± 1.47	34.60 ± 2.06	33.40 ± 1.54	37.80 ± 2.92	34.56 ± 0.95
Calcium (mmol/L)	0	2.51 ± 0.08	2.47 ± 0.16	2.47 ± 0.07	2.25 ± 0.13	2.44 ± 0.05
	7	2.52 ± 0.07	2.39 ± 0.09	2.60 ± 0.08	2.59 ± 0.14	2.54 ± 0.05
	15	2.55 ± 0.08	2.29 ± 0.08	2.48 ± 0.07	2.36 ± 0.14	2.44 ± 0.05
	30	2.46 ± 0.07	2.40 ± 0.15	2.49 ± 0.07	2.32 ± 0.14	2.43 ± 0.05
	45	2.44 ± 0.08	2.48 ± 0.12	2.45 ± 0.06	2.38 ± 0.12	2.44 ± 0.04
Phosphorus (mmol/L)	0	1.16 ± 0.03	1.27 ± 0.14	1.16 ± 0.04	1.25 ± 0.14	1.20 ± 0.04
	7	1.22 ± 0.04	1.25 ± 0.05	1.17 ± 0.06	1.12 ± 0.03	1.19 ± 0.03
	15	1.19 ± 0.04	1.18 ± 0.02	1.20 ± 0.03	1.11 ± 0.01	1.18 ± 0.02
	30	1.20 ± 0.05	1.33 ± 0.06	1.24 ± 0.05	1.13 ± 0.01	1.23 ± 0.03
	45	1.20 ± 0.04	1.17 ± 0.02	1.15 ± 0.03	1.14 ± 0.03	1.16 ± 0.02
Alkaline Phosphatase (mmol/L)	0	189.43±10.71	203.40±8.82	181.80±7.58	188.40±9.07	189.00±4.58
	7	191.57±10.38	204.60±8.41	183.90±7.30	190.40±8.56	190.93±4.41
	15	193.29±10.47	206.60±8.18	185.80±7.51	192.40±8.86	192.81±4.47
	30	188.86±10.48	202.00±8.35	181.30±7.50	187.80±8.86	188.30±4.48
	45	191.29±10.09	204.80±7.85	184.10±7.24	191.20±8.49	191.11±4.32

Table 11(b): *ANOVA of haematobiochemical parameters in animals of different groups at various intervals.*

Parameters	**Day**	**Source of variation**	**Sum of squares**	**Degree of freedom**	**Mean square**	**F value**
Haemoglobin	0	Between groups	4.04	3	1.35	0.38
		Within groups	80.61	23	3.51	
		Total	84.64	26		
	7	Between groups	6.38	3	2.13	0.47
		Within groups	103.41	23	4.50	
		Total	109.80	26		
	15	Between groups	3.60	3	1.20	0.49
		Within groups	55.91	23	2.43	
		Total	59.52	26		
	30	Between groups	0.93	3	0.31	0.13
		Within groups	53.53	23	2.33	
		Total	54.46	26		
	45	Between groups	1.48	3	0.49	0.33
		Within groups	34.65	23	1.51	
		Total	36.13	26		
Packed Cell Volume	0	Between groups	131.29	3	43.76	0.65
		Within groups	1560.11	23	67.83	
		Total1	691.41	26		
	7	Between groups	97.64	3	32.55	0.95
		Within groups	786.21	23	34.18	
		Total	883.85	26		
	15	Between groups	43.64	3	14.55	0.41
		Within groups	812.21	23	35.31	
		Total	855.85	26		
	30	Between groups	80.54	3	26.85	1.19
		Within groups	517.31	23	22.49	
		Total	597.85	26		
	45	Between groups	69.41	3	23.14	0.95
		Within groups	559.26	23	24.32	
		Total	628.67	26		
Calcium	0	Between groups	0.22	3	0.07	1.07
		Within groups	1.60	23	0.07	
		Total	1.83	26		
	7	Between groups	0.16	3	0.05	0.93
		Within groups	1.32	23	0.06	
		Total	1.48	26		
	15	Between groups	0.24	3	0.08	1.46
		Within groups	1.26	23	0.06	
		Total	1.50	26		

Table 11(b): *ANOVA of haematobiochemical parameters in animals of different groups at various intervals (Contd...).*

Parameters	Day	Source of variation	Sum of squares	Degree of freedom	Mean square	F value
	30	Between groups	0.10	3	0.03	0.54
		Within groups	1.46	23	0.06	
		Total	1.56	26		
	45	Between groups	0.03	3	0.01	0.18
		Within groups	1.17	23	0.05	
		Total	1.20	26		
Phosphorus	0	Between groups	0.07	3	0.02	0.55
		Within groups	0.93	23	0.04	
		Total	1.00	26		
	7	Between groups	0.05	3	0.02	0.91
		Within groups	0.45	23	0.02	
		Total	0.51	26		
	15	Between groups	0.03	3	0.01	1.47
		Within groups	0.15	23	0.01	
		Total	0.18	26		
	30	Between groups	0.10	3	0.03	1.88
		Within groups	0.42	23	0.02	
		Total	0.52	26		
	45	Between groups	0.01	3	0.00	0.54
		Within groups	0.16	23	0.01	
		Total	0.17	26		
Alkaline Phosphatase	0	Between groups	1558.29	3	519.43	0.91
		Within groups	13183.71	23	573.21	
		Total	14742.00	26		
	7	Between groups	1432.84	3	477.61	0.90
		Within groups	12193.01	23	530.13	
		Total	13625.85	26		
	15	Between groups	1444.65	3	481.55	0.88
		Within groups	12591.43	23	547.45	
		Total	14036.07	26		
	30	Between groups	1431.87	3	477.29	0.87
		Within groups	12639.76	23	549.56	
		Total	14071.63	26		
	45	Between groups	1428.74	3	476.25	0.94
		Within groups	11661.93	23	507.04	
		Total	13090.67	26		

**(P<0.01); *(P<0.05)

Table 12: *Mean ± SE of time for fracture healing (days) in animals of different groups.*

Variable	**Factors**	**Mean ± S.Em**
Fixator type	Acrylic	46.33 ± 3.83 (12)
	Epoxy	50.87 ± 3.47 (15)
Breed of the dog	Doberman	35.00 ± 0.00 (1)
	Great Dane	65.00 ± 0.00 (1)
	German Shephered	51.67 ± 4.41 (3)
	Labrador	46.25 ± 5.91 (4)
	Mongrel	49.83 ± 4.38 (12)
	Rotweiller	30.00 ± 0.00 (2)
	Spitz	55.25 ± 3.45 (4)
Age group*	0-6 months	37.00 ± 7.68^{a} (4)
	6- 12 months	44.64 ± 4.09^{ab} (11)
	1-2 year	56.67 ± 1.67^{b} (6)
	Above 2 years	56.67 ± 4.01^{b} (6)
Sex	Male	49.89 ± 3.25 (18)
	Female	46.78 ± 4.26 (9)
Treatment groups	Acrylic-Radius/Ulna	46.14 ± 4.72 (7)
	Acrylic-Tibia	46.6 ± 7.08 (5)
	Epoxy-Radius/Ulna	49.8 ± 4.73 (10)
	Epoxy-Tibia	53.00 ± 4.90 (5)
Weight groups	Up to 10 kg	44.00 ± 6.57 (6)
	10-20 kg	50.00 ± 3.84 (13)
	Above 20 kg	50.63 ± 3.83 (8)
Cause of injury	Accident	47.73 ± 3.78 (11)
	Fall from height	47.23 ± 4.09 (13)
	Hit by stick	60.00 ± 0.00 (3)
Time since injury	Up to 5 days	50.07 ± 3.67 (14)
	5-15 days	51.14 ± 4.69 (7)
	Above 15 days	43.33 ± 5.73 (6)
Type of wound	Open	50.14 ± 5.12 (7)
	Closed	48.40 ± 3.03 (20)
Degree of trauma	Slight trauma	47.15 ± 3.16 (20)
	Moderate trauma	55.25 ± 3.45 (4)
	Severe trauma	51.67 ± 8.33 (3)
Bone involved	Radius/Ulna	48.29 ± 3.32 (17)
	Tibia	49.80 ± 4.19 (10)
Overall		48.85 ± 2.56 (27)

Table 12(a): *ANOVA of time of fracture healing (days) in animals of different groups.*

Groups	Source of variation	Sum of squares	Degree of Freedom	Mean square	F value
Fixator type	Between groups	137.01	1	137.01	0.77
	Within groups	4464.40	25	178.58	
	Total	4601.41	26		
Breed of the dog	Between groups	1389.57	6	231.60	1.44
	Within groups	3211.83	20	160.59	
	Total	4601.41	26		
Age group	Between groups	1490.20	3	496.73	3.67*
	Within groups	3111.21	23	135.27	
	Total	4601.41	26		
Sex	Between groups	58.07	1	58.07	0.32
	Within groups	4543.33	25	181.73	
	Total	4601.41	26		
Treatment groups	Between groups	171.75	3	57.25	0.30
	Within groups	4429.66	23	192.59	
	Total	4601.41	26		
Weight groups	Between groups	183.53	2	91.77	0.50
	Within groups	4417.88	24	184.08	
	Total	4601.41	26		
Cause of injury	Between groups	420.92	2	210.46	1.21
	Within groups	4180.49	24	174.19	
	Total	4601.41	26		
Time since injury	Between groups	240.29	2	120.14	0.66
	Within groups	4361.12	24	181.71	
	Total	4601.41	26		
Type of wound	Between groups	15.75	1	15.75	0.09
	Within groups	4585.66	25	183.43	
	Total	4601.41	26		
Degree of trauma	Between groups	245.44	2	122.72	0.68
	Within groups	4355.97	24	181.50	
	Total	4601.41	26		
Bone involved	Between groups	14.28	1	14.28	0.08
	Within groups	4587.13	25	183.49	
	Total	4601.41	26		

**(P<0.01); *(P<0.05)

Vitae

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