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Scientific Article

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Mechanical testing of a steel-reinforced epoxy resin bar and clamp for external skeletal fixation of long-bone fractures in cats

BJ Leitch*†§ and AJ Worth*

Abstract

AIMS: To provide veterinarians with confidence when using a commercially available epoxy resin in external skeletal fixators (ESF), testing was conducted to determine exothermia during curing of the epoxy resin compared to polymethylmethacrylate (PMMA), the hardness of the epoxy resin as a bar over 16 weeks, and the strength of the epoxy resin bar compared with metal clamps in similarly constructed Type 1a ESF constructs simulating the repair of feline long bone fractures.

METHODS: Exothermia of the epoxy resin during curing was tested against PMMA with surface temperatures recorded over the first 15 minutes of curing, using four samples of each product. The hardness of 90 identical epoxy resin bars was tested by subjecting them to cyclic loads (1,000 cycles of 20.5 N, every 7 days) over a 16-week period and impact testing 10 bars every 2 weeks. Ten bars that were not subjected to cyclic loads were impact tested at 0 weeks and another 10 at 16 weeks. Strength of the epoxy resin product, as a bar and clamp composite, was tested against metal SK and Kirschner-Ehmer (KE) clamps and bars in Type 1a, tied-in intramedullary pin, ESF constructs with either 90° or 75° pin placement, subjected to compressive and bending loads to 75 N.

RESULTS: The maximum temperature during curing of the epoxy resin (min 39.8, max 43.0)°C was less than the PMMA (min 85.2, max 98.5)°C ($p<0.001$). There was no change in hardness of the epoxy resin bars over the 16 weeks of cyclic loading ($p=0.58$). There were no differences between the median strength of the epoxy resin, SK or KE ESF constructs in compression or bending when tested to 75 N ($p>0.05$). Stiffness of constructs with 75° pin placement was greater for SK than epoxy resin constructs in compression ($p=0.046$), and was greater for KE than epoxy resin constructs in bending ($p=0.033$).

CONCLUSIONS: The epoxy resin tested was found to be less exothermic than PMMA; bars made from the epoxy resin showed durability over an expected fracture healing timeframe and had mechanical strength characteristics comparable to metal bar and clamp ESF constructs.

CLINICAL RELEVANCE: The epoxy resin ESF construct tested in this study can be considered a suitable replacement for SK or KE ESF constructs in the treatment of feline long-bone fractures, in terms of mechanical strength.

KEY WORDS: *External skeletal fixation, cat, epoxy resin, epoxy, mechanical strength, hardness*

Introduction

Comminuted fractures of the long bones in cats are common as the result of trauma. When a comminuted, diaphyseal fracture cannot be anatomically reconstructed, biological fixation is recommended to minimise additional loss of blood supply to the bone fragments (Aron and Dewey 1992). External skeletal fixation (ESF) is one form of biological fixation and has been successfully used in the management of feline long bone fractures (Langley-Hobbs *et al.* 1996, 1997). The weakest component of a Type 1a (unilateral-uniplanar) ESF frame is reported to be the connecting bar (Aron and Dewey 1992; Reaugh *et al.* 2007).

Traditional linear metal bar and clamp systems used for ESF require an inventory of clamps and are somewhat constrained in the ways they can be applied (Piermattei *et al.* 2006). In contrast, ESF utilising non-metal bar or clamp materials have increased versatility and ease of application (McCartney 1998; De La Puerta *et al.* 2008). Most commonly these systems use a bar and clamp construct of polymethylmethacrylate (PMMA). ESF using PMMA has been shown to be as strong as metal clamps in the construction of various ESF frames, whilst being able to be shaped to non-linearly aligned pin positions (Okrasinski *et al.* 1991; Willer *et al.* 1991). As an alternative to PMMA, epoxy resins have gained popularity in ESF constructions (Roe and Keo 1997; Kumar *et al.* 2012). Like PMMA, epoxy resins have conformation advantages over traditional metal bar and clamp systems, being lighter and more conformable, enabling use in areas where typical ESF are less suited, e.g. the mandible, avian surgery and exotic species, with less complex frameworks

ESF	External skeletal fixator
IM	Intramedullary
KE	Kirschner-Ehmer
PMMA	Polymethylmethacrylate
SEAT	School of Engineering and Advanced Technology

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(Owen *et al.* 2004; Hatt *et al.* 2007; Cetinkaya *et al.* 2011). In cats with comminuted humeral, tibial or femoral fractures, a low-cost, epoxy resin bar and clamp, in a Type 1a ESF with a tied-in intramedullary (IM) pin was reported to be cost effective and simple to apply, with good clinical results (Worth 2007).

To the authors' knowledge, the epoxy resin ESF construct, as reported by Worth (2007), has not been biomechanically compared to traditional, linear, metal bar and clamp ESF constructs. In the current study, three experiments were performed using the resin and ESF construct used by Worth (2007). Epoxy resin is exothermic during curing so the curing temperature characteristics of the resin were determined and compared to PMMA. Temperatures >50°C were considered significant as they can cause thermal damage to tissues (Martinez *et al.* 1997). The hardness of the epoxy resin as a bar was determined by subjecting samples to cyclic loads over 16 weeks, and testing for changes in hardness over time. The strength and stiffness of the epoxy resin product when used as a bar and clamp in a Type Ia ESF with a tied-in IM pin was tested against equivalent constructs using metal clamp and bar systems. The constructs were tested to 75 N loads and the proportion failing assessed at both this maximum and at 15 N, as Manter (1938) and Kaya *et al* (2006) found that the hindlimb of a 5 kg cat was subjected to 20 N axial compression loading and 8 N cranio-caudal bending load when at a walk.

The null hypotheses were that the maximum surface temperature during curing of the epoxy resin would be less than with PMMA; that there would be no change in the hardness of the epoxy resin bars over time, and that there would be no difference in strength and stiffness between epoxy resin ESF constructs and equivalent constructs using metal clamp and bar systems, when tested in axial compression and cranio-caudal bending.

Materials and methods

The epoxy resin used throughout this experiment was Selley's Knead-It Steel (Orica NZ Ltd, Newmarket, Auckland, NZ). It is a two-part epoxy resin putty polymer of bisphenol A-epichlorhydrin and tri(dimethylaminomethyl)phenol that is activated by kneading the two components which are presented as a roll with the hardener surrounded by the epoxy resin. Manufacturer packaging states after kneading for 1 minute the product hardens within 10 minutes and can be machined after an hour. It is a non-sterile product available in hardware stores throughout Australasia.

Surface temperatures of epoxy resin during curing

The surface temperatures of equal volumes of PMMA and epoxy resin were recorded during the first 15 minutes of their curing phase. The experiment was performed in a controlled temperature (21°C) fume hood. PMMA (Cowslips; Giltspur Scientific Ltd, Ballyclare, Northern Ireland) was mixed as per the manufacturer's directions and poured into plastic 20 mL ice cube tray wells when in a liquid state. Blocks of epoxy resin, 20 cm^3 in size, were kneaded per the manufacturer's directions for 1 minute to a smooth putty with homogenous colour and placed in ice cube wells as for the PMMA. A thermometer (Q1437 digital thermometer; Dick Smith Electronics, Sydney, Australia) with wire thermocouples was taped to a 1 cm^2 piece of aluminium foil pressed into the surface of the PMMA and epoxy resin samples so that heat was conducted through the aluminium to the thermocouple and the thermocouple was not permanently embedded in the material (Supplementary Figure 1[1]). Ambient fume hood temperature was recorded as the base value before mixing. Temperature of the samples was measured after 2 minutes, following the attachment of the thermocouple, then every 30 seconds as the products cured until 15 minutes after initial sample preparation. The test was performed four times for each material. The data were used to determine the maximum temperature for each sample and the duration of surface temperatures >60°C.

Hardness of epoxy resin bars

Construction

Epoxy resin bars, 100 mm long and 9.5 mm in diameter, were constructed to test for changes in hardness when subjected to cyclic loads over 16 weeks; 90 bars had a K-wire embedded, 20 did not. Epoxy resin was kneaded as per the manufacturer's instructions and bars were created by moulding lengths within a 100 mm-long split aluminium pipe with an internal diameter of 10 mm. The pipe was lined with plastic film to prevent adhesion and the bars were removed after 30 minutes. A K-wire was embedded in 90 bars prior to moulding to mimic a fixation pin: 50 mm lengths of 1.6 mm K-wire were bent 90° mid-length and placed within the bar at one end so that 25 mm of the K-wire ran distally down the middle of the bar and 20 mm protruded perpendicular to the bar, 10 mm from the end of the bar (Figure 1). All the bars were precision lathed to 100 mm long and 9.5 mm diameter by the engineering department, School of Engineering and Advanced Technology (SEAT), Massey University (Palmerston North, NZ). All bars were

Figure 1. Epoxy resin bar (100 mm×9.5 mm) with pin inserted for cyclic load testing. The pin is a 1.6 mm K-wire pin, 50 mm-long, bent at 25 mm and moulded into the middle of the bar with 20 mm of the K-wire exposed for load placement.

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stored in a sealed plastic container in a room with temperature maintained at 21 (±1)°C when not being tested.

Cyclic loading

The bars with K-wire (resin+pin) were subjected to weekly cyclic loads for up to 16 weeks using a custom jig from SEAT (Supplementary Figure 2[2]). A 20.5 N weight impacted the exposed pin 10 mm from the resin bar 90 times per minute, for 1,000 cycles, every 7 days. The 20 epoxy resin bars without a pin did not undergo cyclic loading.

The load and number of cycles were designed to approximate the activity of a cat confined over a 4-month post-operative period during healing of a long-bone fracture. This exceeds the previously reported duration of ESF placement in feline femoral fractures of up to 13 weeks (Langley-Hobbs *et al.* 1996; Worth 2007). An assumption was made that the forces and activity levels were constant throughout the testing period. The cyclic load was comparable to reported loading of the feline limb during walking (Manter 1938; Kaya *et al.* 2006).

Impact testing

Every 2 weeks, starting 48 hours after bar construction (0 weeks), 10 randomly selected resin+pin bars were impact-tested for hardness. The remaining bars continued weekly cyclic loading for up to 16 weeks. Thus, the bars tested at 2 weeks had undergone 2,000 cyclic loads while those tested at 16 weeks had undergone 16,000 loads. Ten of the bars without a pin were impact-tested for hardness at 0 weeks, and 10 at 16 weeks.

Impact testing was performed using a Zwick Impact Test Pendulum (Zwick Roell, Ulm, Germany; Supplementary Figure 3[2]). The device was set up as a three-point impact test using a wedge-head pendulum to provide the kinetic impact energy to break the bars set across the bottom of the pendulum's swing on two platforms either side of the 50 mm gap for the pendulum. The pendulum selected provided 2.2 J at impact. Hardness (J/mm^2) was calculated by subtracting the residual energy (J), recorded on the pendulum, after breaking the bar, from 2.2 J and dividing that figure by the measured cross-sectional area (mm^2) of the bar at the impact point. Data were assessed for changes in the hardness of the bars over time for bars with and without pins.

Comparison of ESF constructs

The strength of the epoxy resin bars in ESF constructs was compared with mini SK and small KE clamps (Imex Veterinary Inc., Longview, TX, USA) using a model of a mid-diaphyseal, non-load sharing (comminuted), femoral fracture. Acetal-C plastic rods (Dotmar Engineering Plastics Ltd, Palmerston North, NZ) were selected as the bone substitute in the femoral fracture models due to its previously reported use and characteristics (Gibson *et al.* 2008b).

ESF construction

Femoral bone model dimensions were based on radiographs of feline femurs from clinical cases at the Massey University Veterinary Teaching Hospital (Palmerston North, NZ) and the studies by Manter (1938) and Gibson *et al.* (2008a). To create the bone models, 8 mm diameter solid acetal rod was cut into 90 pieces, each 50 mm in length. Each piece represented half of a femur. Every piece was then mounted in a drill-press and cored to 45 mm depth with a 4.5 mm drill bit leaving a 5 mm solid end to represent metaphyseal or epiphyseal bone and a wall width of 1.75 mm. The fractured bone model consisted of two rod sections with cored ends facing each other separated by the experimental fracture gap. The ESF was constructed to this model.

Two 1.6 mm-K-wire transfixing pins were placed transversely in each rod segment, 10 mm from either end of the rod, into pre-drilled 1.5 mm holes so that they fully engaged the far wall. The holes were offset by 1 mm from the rod centre. The pins were inserted at 90° to the long axis of the rod in 30 ESF constructs and at 75° (convergent) to the long axis of the rod in 15 constructs (Figure 2). Convergent pin insertion is considered important to increase pin pull-out (slippage) resistance when non-threaded ESF pins are used (Bennett *et al.* 1987). The gap between the two rod sections (inter-fragmentary gap) was set at 10 mm for the 90° constructs, and 8 mm for the 75° constructs, due to pin interference with the testing device jigs at 10 mm. A custom template was used to align the rod sections and set the gap during construction (Figure 2).

A 1.6 mm IM pin was placed down the centre of both sections of the acetal rods, through a 1.5 mm pre-drilled hole in the end of one section and so that it made firm contact with the solid end of the other. It was offset 1 mm from centre to enable IM pin placement without interference with the transfixing pins. The solid end of one of the rod sections (to be used as the distal segment of the model) was domed by precision lathe. At the other end, a domed aluminium cap with a slit was placed over the exposed IM pin, that allowed compressive force to be applied to the acetal rod, avoiding the IM pin. The use of an end-cap has been reported previously (Van Wettere *et al.* 2009). Pin placement, coring of the acetal rods and the spilt cap are shown in Supplementary Figure 4[2].

The 45 models were divided into three groups for the three different types of bar and clamp ESF construct being tested so that each

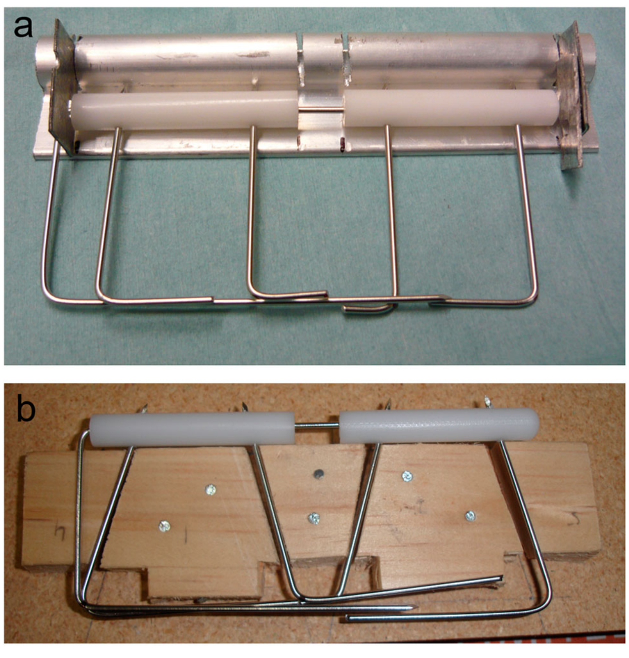

Figure 2. External skeletal fixator constructs used to model fractured femurs showing the configuration of transfixing pins, inserted at (a) 90° and (b) 75° to the long axis, and position of intramedullary pins, parallel to the long axis.

[2]https://doi.org/10.1080/00480169.2018.1443406

bar and clamp system had 10 constructs with transfixing pins at 90° and five with pins at 75°.

The metal connecting bars for the SK and KE clamps were 3.2 mm stainless steel IM pins cut to a length of 110 mm. The epoxy resin bars were constructed to 100 mm length. Two sets of five clamps of each of the SK and KE clamps were used in the study so that each set of clamps was used in 7–8 models. All the constructs were fabricated by the same investigator (BL) and the clamps tightened by hand using a 7 mm wrench without a torque limiter.

The structure of the three different ESF constructs is shown in Figure 3. The distance from the centre of the connecting bar to the surface of the acetal rods was set at 35 mm, based on estimations of soft tissue and muscle mass from radiographs at Massey University Veterinary Teaching Hospital. To make each epoxy resin bar, a 3.5 cm length of the epoxy resin (18–20 mm diameter) was cut and kneaded per manufacturer's instructions, then rolled out and pressed around the bent pins and moulded within two halves of an aluminium pipe (internal diameter 10 mm, length 100 mm) lined with plastic film (to prevent adhesion) for 10 minutes until hardened. Any excess epoxy resin was trimmed away. This created a steel-reinforced epoxy resin bar. All epoxy resin constructs were fabricated >1 day prior to testing. For the SK and KE constructs the IM pin was tied-in to a clamp on the proximal end of the bar (Figure 3).

To monitor epoxy resin bar uniformity, the 3.5 cm sections of unmixed epoxy resin cut for each bar were weighed before activation and the excess trimmings subtracted to determine the epoxy resin in each bar. Epoxy resin bar composite weights were also measured after the construct had completed testing. For this the pins were cut at the epoxy resin surface and the epoxy resin bar with embedded pins was weighed as one composite unit. Construct weights were measured using digital scales (HP-30K; A&D Company Ltd., Tokyo, Japan). One each of the SK and KE constructs (five clamps) were also weighed. All the metal bars used were weighed separately and the mean calculated. The combined weights (five clamps plus mean metal bar weight) are reported for comparison with the epoxy resin composites.

Construct testing

Two tests were performed on each ESF construct; axial compression and cranio-caudal bending, to determine the strength (maximum tolerated load) and stiffness (rate of change under load) of the constructs. Testing was performed in a Hounsfield Tensometer (number 8353, Tensometer Limited, Croydon, UK). This is a manual load testing machine where a screw drive applies load (at a rate determined by the operator), recorded via a mercury column scale coupled with the load plate and transferred to a drum holding graph paper to create load-displacement curves (Figure 4). Different load plates can be used for different maximum loads and different jigs allow compression, traction, shear, rotation or bending forces to be applied.

Compression testing was performed first, with the inter-fragmentary gap recorded using a digital Vernier calliper (Dick Smith Electronics, Sydney, Australia) when each ESF construct was set in the testing machine before loading. During testing the calliper tips were set within the inter-fragmentary gap so that movement of the callipers when a change of 10% was reached indicated the endpoint. The constructs were placed within the tensometer so that compressive load was applied to the ends of the rods held secure in concave aluminium buttons glued onto the load surfaces to prevent slippage and shear forces (Figure 5). Load was applied at 3 mm/minute until 75 N or a gap change >10% was recorded.

The second test was cranio-caudal bending. The constructs were placed in a 4-bar jig made to hold the constructs with two cross-bars on each section of acetal rod (Figure 4). This converted a tensile load (distraction of the two load arms) into a bending load on the construct through loads to the acetal rods about the two cross-bars adjacent to the inter-fragmentary gap.

The tensometer was set to place a maximal load of 75 N in each test so it was possible for constructs to not fail (construct strength exceeded 75 N load). The maximum tolerated load (strength) and rate of change under load (stiffness) were recorded for each construct using pre-determined end-points. These failure end-points were yield, a bending angle >5°, slippage and gap change >10%. Endpoints were recorded by either assessing points on the plotted load-displacement graphs (yield, bending and

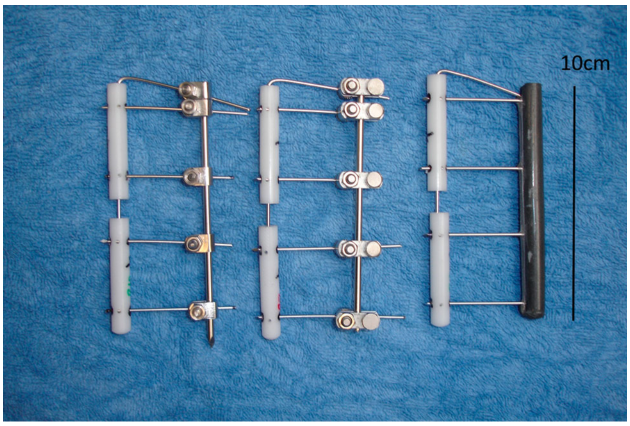

Figure 3. The three different external skeletal fixator constructs as made with 90° transfixing pin alignment. The constructs from left to right are small Kirschner-Ehmer (KE) and mini SK clamps, and epoxy resin bars. The intramedullary pin is tied proximally for the KE and SK constructs but incorporated into the bar for the epoxy resin construct. The scale bar on right is 10 cm.

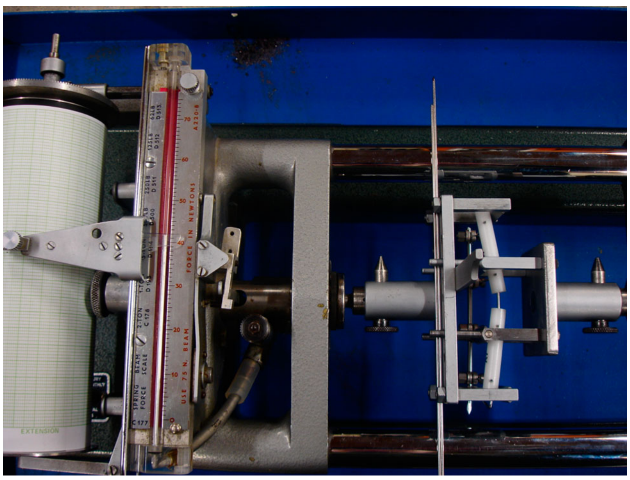

Figure 4. An external skeletal fixator construct in the Hounsfield tensometer 4-point, cranio-caudal bending, test jig. This shows the mercury column and rotating graph paper for plotting the rising mercury column as load is applied. Distracting the load arms applies bending loads to the acetal rod sections as the inner and outer arms move in opposite directions.

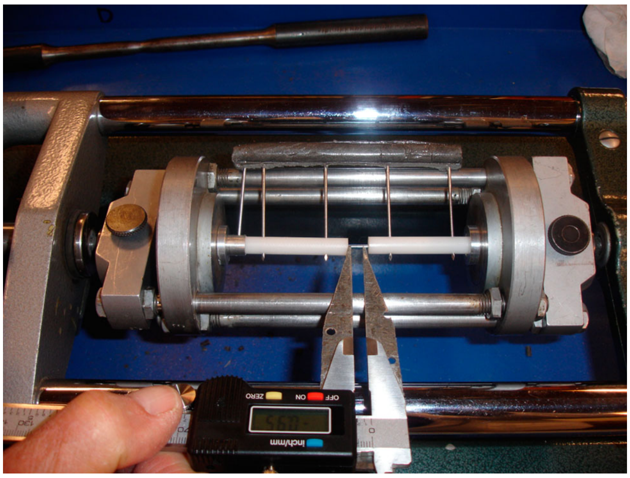

Figure 5. Digital calipers positioned in the inter-fragmentary gap of an external skeletal fixator epoxy resin construct for measurement of gap reduction during compression testing.

slippage) after each test, or by digital calipers during testing (gap change) as described above.

Yield was identified by a change in the load-displacement curve to a horizontal maximum and indicated a change from elastic to plastic deformation of the construct, representing a permanent deformation of the ESF. Bending was only measured in the cranio-caudal bending tests and was calculated from the graphed load-displacement data to determine when a >5° change in the acetal rod section alignment across the gap had occurred. Slippage was a short flattening of the curve (step) followed by a return to the previous curve and indicated a loss of grip of the pins within the acetal rods or within the clamps or epoxy resin. The end-points of 10% gap change and 5° angle changes were selected as they indicate stress or strain on material within a healing callus that would not be tolerated by cartilage or chondrocytes (Piermattei *et al.* 2006). Construct failure was assessed at 75 N for both tests and at 15 N for the cranio-caudal bending tests as this compared the constructs against biomechanical hindlimb bending loads reported by Manter (1938) and Kaya *et al.* (2006).

Statistical analyses

Data were analysed using Minitab (version 15; Minitab Inc., State College, PA, USA) and R (version 2.8.1; R Foundation for Statistical Computing, Vienna, Austria) statistical programs. The surface temperature data were analysed using Student's *t*-test to compare the mean maximum temperatures between PMMA and epoxy resin samples during curing.

The hardness of epoxy resin bars measured by impact testing were compared between testing times, and between resin+pin bars and bars without pins, using Student's *t*-tests for normally distributed data, and Kruskal-Wallis and Wilcoxon rank sum tests if data were not normally distributed.

The maximum tolerated load (strength) and rate of change under load (stiffness) recorded for each ESF construct were compared between the three different construct types (resin, SK, KE), for the two different pin configurations (75° and 90°), and the two different loads (compression and cranio-caudal bending) using Kruskal-Wallis and Wilcoxon rank sum tests, as data were not normally distributed.

Results

Surface temperatures

All the PMMA samples reached maximal temperatures at 4 minutes whereas the interval to maximum temperatures for epoxy resin samples varied between 8–9 minutes. The mean maximum surface temperature of the PMMA samples was 90.5 (min 85.2, max 98.5)°C, which was hotter than the mean 41.6 (min 39.8, max 43.0)°C for epoxy resin samples ($p<0.001$). PMMA samples were recorded at temperatures >60°C for 5–9.5 minutes, whereas epoxy resin never reached 60°C (Figure 6).

Epoxy resin hardness

Results of the impact testing of resin+pin bars after cyclic loading every 2 weeks for 16 weeks are shown in Figure 7. There was no change in mean hardness of the resin+pin constructs between weeks 0 and 16, despite repeated cyclic loading ($p=0.58$). For

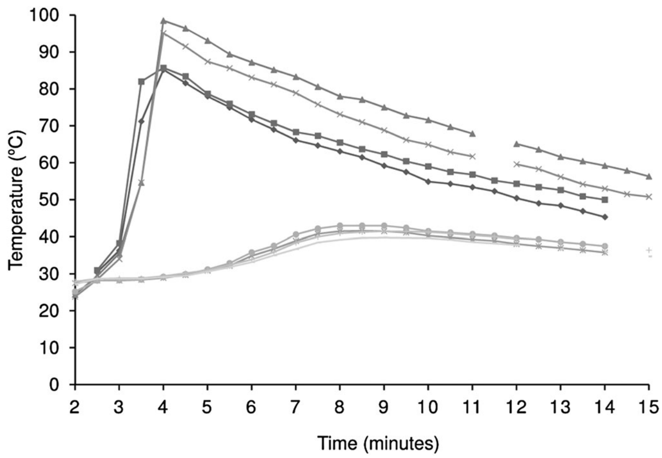

Figure 6. Surface temperature (°C) of samples of polymethylmethacrylate (dark grey lines; n=4) and epoxy resin (light grey lines; n=4) measured from 2–15 minutes after samples were mixed, during curing.

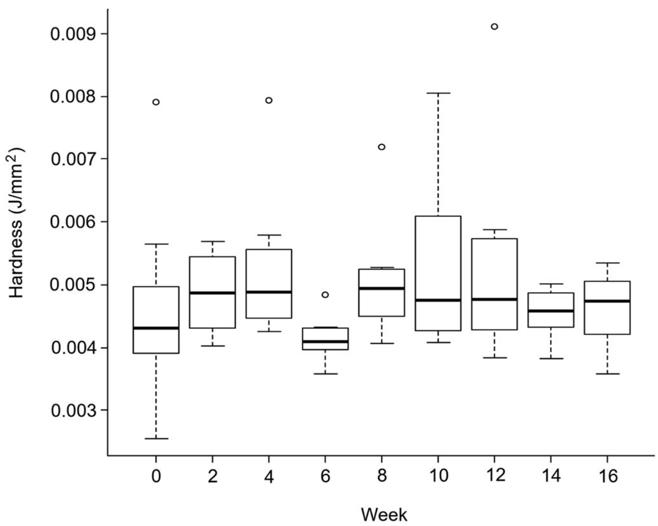

Figure 7. Box and whisker plots of the hardness (J/mm^2) of epoxy resin constructs with a K-wire pin, measured every 2 weeks (n=10 per test) after cyclic loading once per week. Hardness was calculated from the energy required to break the epoxy resin bar using a weighted pendulum wedge. The median value is indicated by the bold line, the 75th and 25th percentiles are indicated by the upper and lower edges of the boxes, respectively, the minimum and maximum values indicated by the whiskers, with outliers shown by open circles.

the bars without pins the mean hardness at 0 weeks (0.0045 (SD 0.00092) J/mm^2) tended to be less than that measured at 16 weeks (0.0048 (SD 0.00094) J/mm^2) (p=0.08). The mean hardness of the resin+pin bars did not differ compared with the bars with no pins at either 0 weeks (0.0046 (SD 0.00142) *vs.* 0.0045 (SD 0.00092) J/mm^2; p=0.55) or 16 weeks (0.0046 (SD 0.00053) *vs.* 0.0048 (SD 0.00094) J/mm^2; p=0.37).

Weights of the ESF constructs

The mean weights of the three ESF construct types (connecting bar and clamps) were 38.7 (min 38.5, max 38.9) g for SK constructs, 34.5 (min 34.3, max 34.7) g for KE constructs and 23.9 (min 22.7, max 25.1) g, for epoxy resin constructs. The mean amount of epoxy resin used in each bar was 20.4 g.

Strength of ESF constructs

Table 1 shows the load at failure and mode of failure for each ESF construct. Overall 27/45 (60%) constructs failed in the compression tests, with 20/30 (67%) of the constructs with 90° fixation pins failing; 16 of these failures were due to slippage, most likely at the pin-plastic interface, and four were due to gap reduction >10%. Of the constructs with 90° fixation pins, 5/10 of the resin constructs failed, 6/10 SK constructs failed, and 9/10 KE constructs failed. Of the constructs with 75° fixation pins, 7/15 (47%) failed, with six due to gap reduction >10%. In the cranio-caudal bending tests every construct failed, with similar numbers of bending and yield failures for the different construct types, except for the KE constructs with 75° fixation pins, which only failed by yield (5/5).

The median and lowest load at failure and numbers of constructs not failing for each ESF construct type are shown in Table 2. The distribution of the loads at failure for each construct type in each test is shown in Figure 8. There was no difference in median load at failure between the ESF construct types when tested using axial

Table 1. Load at failure and failure modes[a] for individual external skeletal fixator (ESF) constructs made using epoxy resin bars (Resin), mini SK or small Kirschner-Ehmer (KE) clamps, tested in axial compression or cranio-caudal bending, with fixation-pins at 90° or 75°. Loads were applied up to a maximum of 75 N and values of 75 indicate no failure (NF) of that construct.

	90°				75°			
	Compression		Bending		Compression		Bending	
Construct	Failure load (N)	Failure mode	Failure load (N)	Failure mode	Failure load (N)	Failure mode	Failure load (N)	Failure mode
Resin								
1	39	Slip	13	Bend	75	NF	18	Bend
2	47	Slip	11	Bend	75	NF	18	Bend
3	75	NF	12	Bend	75	NF	18	Yield
4	75	NF	18	Yield	43	Slip	13	Yield
5	71	Gap	16	Yield	75	NF	15	Yield
6	75	NF	17	Yield				
7	56	Slip	12	Bend				
8	75	NF	15	Yield				
9	52	Slip	14	Yield				
10	75	NF	9	Bend				
SK								
1	49	Slip	12	Bend	75	NF	20	Yield
2	26	Slip	12	Bend	70	Gap	18	Yield
3	75	NF	15	Bend	75	NF	21	Bend
4	43	Slip	14	Bend	57	Gap	18	Bend
5	75	NF	12	Yield	63	Gap	18	Bend
6	75	NF	11	Bend				
7	64	Slip	17	Yield				
8	36	Slip	13	Yield				
9	75	NF	12	Yield				
10	54	Slip	15	Yield				
KE								
1	45	Slip	13	Yield	75	NF	11	Yield
2	49	Slip	15	Bend	24	Gap	18	Yield
3	36	Slip	6	Bend	53	Gap	17	Yield
4	71	Gap	14	Bend	75	NF	18	Yield
5	75	NF	9	Yield	62	Gap	19	Yield
6	70	Gap	5	Bend				
7	72	Gap	15	Yield				
8	56	Slip	12	Bend				
9	48	Slip	9	Bend				
10	23	Slip	11	Bend				

[a]Determined by direct measurements or calculated from the load-displacement curves, defined as bending > 5° calculated from load-displacement curves (Bend); inter-fragmentary gap change >10% (Gap); slippage indicated by sudden horizontal section in plot of load-displacement curve (Slip), or yield indicated by change in load-displacement curve profile as plastic deformation begins (Yield)

Table 2. Number of external skeletal fixator (ESF) constructs made using epoxy resin bars (Resin), mini SK or small Kirschner-Ehmer (KE) clamps that did not fail[a] when tested in axial compression and cranio-caudal bending with fixation-pins at 90° or 75°, with the median and lowest load at failure.

		Axial compression			Cranio-caudal bending		
			Failure load (N)			Failure load (N)	
Pin angle	Construct	Non-failed	Median	Lowest	Non-failed	Median	Lowest
90°							
	Resin	5/10	73	39	4/10	13	9
	SK	4/10	59	26	3/10	12	11
	KE	1/10	52	23	2/10	11	5
75°							
	Resin	4/5	75	43	4/5	18	13
	SK	2/5	70	57	5/5	18	18
	KE	2/5	62	24	4/5	18	11

[a]Number of non-fail constructs are shown for 75 N in axial compression (the maximum test value) and the lower physiological load (15 N) in cranio-caudal bending (Manter 1938; Kaya *et al.* 2006).

compression or cranio-caudal bending, with transfixing pins at 75° or 90° (p>0.05).

Stiffness of ESF constructs

The median rates of change under load for each ESF construct type in each test are shown in Table 3. There was no difference between the construct types with fixation-pins at 90° for either axial compression or cranio-caudal bending tests (p>0.05). For constructs with fixation-pins at 75° in axial compression the stiffness of the SK constructs was greater than the epoxy resin and KE constructs (p=0.046). In cranio-caudal bending the stiffness of the KE constructs was greater than the SK and epoxy resin constructs (p=0.033).

Discussion

This study shows that the epoxy resin, which is readily available and cost-effective, is thermally safe, durable and mechanically as strong as the traditional linear, metal ESF systems when used as a combined bar and clamp for ESF construction in a feline long bone fracture model. The epoxy resin bar diameter chosen for

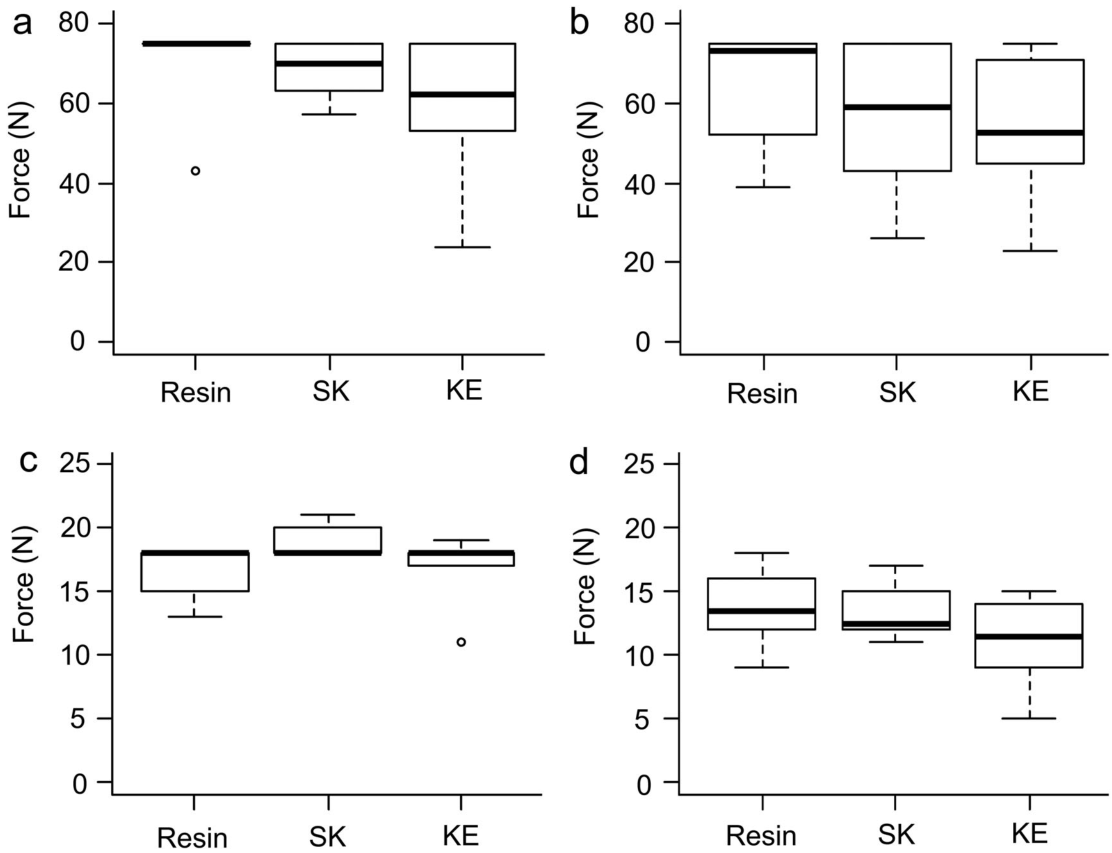

Figure 8. Box and whisker plots of the load at failure (N) of external skeletal fixator (ESF) constructs made using epoxy resin bars (Resin), mini SK or small Kirschner-Ehmer (KE) clamps when tested in (a and b) axial compression and (c and d) cranio-caudal bending with fixation-pins at 90° (b and d) or 75°(a and c). The median value is indicated by the bold line, the 75th and 25th percentiles are indicated by the upper and lower edges of the boxes, respectively, the minimum and maximum values indicated by the whiskers, with outliers shown by open circles.

Table 3. Median (25th and 75th percentiles) rate of change under load (N/mm) of external skeletal fixator (ESF) constructs made using epoxy resin bars (Resin), mini SK or small Kirschner-Ehmer (KE) clamps, with fixation-pins at 90° or 75°, in axial compression and cranio-caudal bending testing to 75 N.

	90°		75°	
Construct	Compression	Bending	Compression	Bending
Resin	75.4	37.1	30.0^{w}	37.0^{y}
	(60.0, 81.1)	(30.5, 45.7)	(21.4, 60.0)	(34.5, 44.1)
SK	75.4	33.0	81.1^{x}	47.6^{y}
	(69.8, 96.8)	(30.5, 44.1)	(69.8, 81.1)	(47.6, 47.6)
KE	81.1	25.9	38.2^{w}	69.8^{z}
	(81.0, 96.8)	(23.2, 33.6)	(21.8, 53.6)	(60.0, 96.8)

^{wx} Values within column differ (p=0.046)
^{yz} Values within column differ (p=0.033)

this experiment (9.5–10 mm) was based on the bar tested by Roe and Keo (1997) and determined to be equal to a 3.2 mm diameter metal bar. The epoxy resin constructs were lighter than the metal constructs tested and sample surface temperatures increased gradually allowing more time to safely shape the product by hand as it cured. Durability testing found that there were no significant changes in the hardness of the epoxy resin bars over time with cyclic loading. The epoxy resin ESF constructs compared favourably in strength with the metal ESF constructs when tested to 75 N in axial compression and cranio-caudal bending with differences only noted in construct stiffness.

The mean maximal surface temperature of the epoxy resin samples was significantly lower than the PMMA samples and never exceeded 50°C (determined to be thermally damaging to tissues, Martinez *et al.* 1997), whereas the surface temperature of the PMMA samples exceeded 80°C. This lower maximum temperature makes epoxy resin a more usable product for hand construction of ESF bars, and recorded temperatures were similar to the temperature profiles reported for another epoxy resin in ESF models for canine fractures (Tyagi *et al.* 2014). Any effect of these temperatures on tissues was not determined by this experiment.

The durability testing was performed over a timeframe comparable with ESF placement in feline femoral fractures (Langley-Hobbs *et al.* 1996; Worth 2007) and with loads comparable to feline hindlimb loads at a walk (Manter 1938; Kaya *et al.* 2006). The hardness of the epoxy resin bars stored for 16 weeks prior to impact testing did not differ from bars tested at 0 week, indicating that the material did not deteriorate as a function of time. Bars with an embedded K-wire, cyclically loaded 16,000 times over 16 weeks, had no difference in hardness compared with the constructs that had been impact tested with no cyclic loading either at week 0 or week 16 indicating that the epoxy resin bar was durable and able to tolerate repetitive cyclic loads.

The ESF construct design (Type 1a with a tied-in IM pin using two 1.6 mm K-wire transfixing pins per segment) was based on constructs reported by Worth (2007) for low cost constructs using only smooth pins. Strength testing applied 75 N loads to the acetal rod segments of every construct in a non-destructive, monotonic-loading fashion in both axial compression and four-point, cranio-caudal bending. This load is higher than those reported *in vivo* by Manter (1938) and Kaya *et al.* (2006) who found that the hindlimb of a 5 kg cat would be subjected to loads of approximately 20 N compression and 8 N bending at a walk. Axial compression tests indicated there was no difference between the three construct types. The lowest failure load recorded was 39 N for the resin constructs and the median failure load was >70 N. These values are all greater than the *in vivo* load. All constructs failed below 75 N in cranio-caudal bending loads and only 9/30 constructs with 90° fixation pins met or exceeded 15 N (twice the expected load) in the cranio-caudal bending test as shown in Table 2. Fewer constructs with 75° fixation pins failed at 15 N loads than constructs with 90° fixation pins, with only two failing below 15 N. This indicates some tolerance to the loads reported *in vivo* by constructs with convergent pins. Similar constructs have been successfully used in hindlimb fractures of cats. Worth (2007) had success in 7/8 cases treated with similar epoxy resin constructs and Langley-Hobbs *et al.* (1996) had successful outcomes in 91% of femoral fractures using similar metal constructs. We believe these strength test results support the use of the epoxy resin bar and clamp ESF as a substitute for mini SK and small KE clamp ESF systems and support construction using convergent pins.

The modes of failure detected in this study were slippage, yield (exceeded elastic deformation), gap reduction >10% and bending >5°. No model failed by breakage of components. Visual assessment of all epoxy resin bars after testing did not find any evidence of cracking indicating that at the loads tested, steel-reinforced epoxy resin bars of 10 mm diameter are durable.

Slippage within the ESF constructs, evidenced by a flat section of load curve followed by a return to the previous curve profile, occurred in all three construct types with 90° fixation pins in compression testing. The slippage issue, likely at the pin-/acetal rod interface, could have been addressed by using threaded pins (Lewis *et al.* 2001), or by using converging pin techniques (Bennett *et al.* 1987). In the ESF constructs with fixation pins placed at 75° there was only one incidence of slippage. If finances restrict the surgeon to the use of smooth, non-threaded pins, then placing them in a convergent manner is recommended. Parallel pin construction could not be recommended as suitable to tolerate bending forces in the ESF constructs tested. It is not known whether using a bone model material different from the acetal plastic bone substitute material, used in this study would have resulted in less slippage.

Two metal clamp systems were used in this study (mini SK and small KE). Previous work has identified differences in the performance of these systems in their larger sizes (Lewis *et al.* 2001; White *et al.* 2003). No difference in the strength of the metal constructs was found when compared to the epoxy resin constructs in these tests. Another study found that clamp performance deteriorates with repeat use (Gilley *et al.* 2009). This deterioration was reported at supra-physiological loads. There did not appear to be a trend towards weaker constructs within the SK or KE groups in this study with re-use of clamps.

Reaugh *et al.* (2007) found that Type Ia ESF are poorly resistant to bending forces applied perpendicular to the plane of the implant, which in this experiment was the cranio-caudal bending load the constructs were subjected to. It has also been reported that the IM pin provides most of the stiffness in cranio-caudal bending of Type Ia with IM pin constructs (Van Wettere *et al.* 2009), so the failure noted at similar loads by the different ESF constructs in our experiment may be due to the stiffness profile of the 1.6 mm IM pin.

Stiffness values were determined from the load-displacement curves. There were no differences in stiffness between epoxy resin, SK or KE constructs when they were constructed with 90° fixation pins, but there were differences between constructs with 75° fixation pins. In cranio-caudal bending, the epoxy resin constructs were less stiff than the KE constructs but not different from SK constructs. Under axial compression, the SK constructs were stiffer than the epoxy resin constructs. It is not known whether these differences in stiffness are clinically significant however the stiffness of an ESF construct can be increased in practice by increasing pin size, or number of fixation pins in each segment, or increasing IM pin size and bar thickness (Aron and Dewey 1992; Palmer *et al.* 1992; Shahar and Shani 2004).

The epoxy resin used in this study to replace the clamps and bars is a commercially available epoxy resin polymer sold in hardware stores throughout Australasia. It has advantages over PMMA in its handling; the lack of a liquid phase, moderate exothermia and its non-volatile nature. Its disadvantage compared to metal constructs is that it cannot be adjusted once it has set and any correction of the ESF requires fracturing the epoxy resin and resetting with further epoxy resin. Because it is initially a soft dough, steps need to be taken to secure the fracture in reduction until the epoxy resin sets. Options include bending the fixation pins towards the fracture site after placing in the bone, as was done in this study, and joined temporarily with the help of adhesive tape or wire after which the epoxy resin can be more easily applied (Kumar *et al.* 2012; Tyagi *et al.* 2014). Alternatively a temporary KE or SK connection bar and clamp extension can be used beyond the epoxy resin for the 10–15 minutes until the epoxy resin sets, with the pins cut flush on the outside surface of the epoxy resin bar once set. The limb could also be maintained in a hanging frame while the epoxy resin is applied around the pins, allowing manipulation of the limb and epoxy resin bar, as it sets, to optimise limb alignment.

We propose that the method of epoxy resin bar and clamp construction of ESF has relevance for veterinary practitioners with a low orthopaedic case load. Epoxy resin ESF can be applied using this technique requiring only a good supply of IM pins and K-wires. Larger bars can be constructed that may be reinforced with an IM pin. Although not part of this study, centerface and interface positive profile fixation pins could be used and would provide increased security over smooth K-wires. Non-linear construction could also accommodate fixation pins that are off-line. Testing in this study was limited to a construct with an even diameter, straight rod shape. Variation in bar shape and diameter consistency may affect the strength of epoxy resin constructs and must be considered against these results.

In conclusion, we have demonstrated that the maximum surface temperature during curing of the epoxy resin was less than with PMMA; that the hardness of the epoxy resin did not change over 16 weeks and that there was no difference in strength between epoxy resin ESF constructs and equivalent constructs using metal clamp and bar systems. The epoxy resin tested can replace SK and KE metal constructs when a 10 mm diameter epoxy resin bar is constructed with convergent fixation pins and a tied-in IM pin. Epoxy resin constructs are simple to make, durable and allow infrequent orthopaedic surgeons a degree of tolerance in their pin placement that may not be available with SK and KE constructs.

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