In vitro heat transfer from epoxy polymer and poly(methyl methacrylate) to fixation pins: recommendations to avoid tissue damage in free-form external skeletal fixation

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ABSTRACT: External skeletal fixation has been used for the management of fractures of many types of bone. The use of polymeric free-form connecting bars in external fixators has become widely used in veterinary orthopaedics because of its versatile forms of frame construction and its relative low costs. Determining thermal-transfer to trans fixation pins during polymerisation of poly(methyl methacrylate) and epoxy putty polymers used for free-form external skeletal fixation connecting bars is important for avoiding temperatures of more than 47 °C, which would cause thermal soft tissue injury. Therefore, thermal transfer to trans fixation pins was measured *in vitro* during the polymerisation phase of these polymers. We used trocar-pointed pins of different diameters that punctured one wall of a connecting tube, resulting in the tip of the trocar-pointed pin reaching the centre of the tube. The FLUKE® VT02 infrared digital camera was then used to measure heat transfer to the pins at 1 or 2 cm from poly(methyl methacrylate) or epoxy putty. The polymerisation temperatures of these polymers yield a potentially dangerous level of heat for soft and hard tissue. This was observed in almost all the experimental conditions tested. On the other hand, epoxy putty transfer to the pins did not cause the temperature to reach 47 °C at any time or in any of the setups examined. Poly(methyl methacrylate) did reach more than 47 °C and remained at that level for more than 1 min at 1 cm from the polymer. This acrylate exhibited polymerisation temperatures higher than epoxy and its heat transfer to the pins was potentially dangerous if used at less than 1 cm from soft or hard tissue.

Keywords: epoxy putty; bone necrosis; exothermic polymerisation; infrared digital image

List of abbreviations

AP = alkaline phosphatase, **EPOX** = epoxy putty, **ESF** = external skeletal fixation, **FOV** = field of view, **FPA** = focal plane array, **HTI** = highest temperature interval, **IR** = infra, **PMMA** = poly(methyl methacrylate), **Tmax** = maximum polymerisation temperature

External skeletal fixation (ESF) has been used for the management of fractures of different severities in many different types of bone. This technique involves a process of bone structure alignment and stabilisation, with pins that attach the bone fragments to an external stiff frame (Roe 2005). The use of external fixators for the treatment of open fractures, non-union, arthrodesis and growth deformity corrective surgery are commonly used in veterinary orthopaedics (Ozsoy and Altunatmaz 2003; Theyse et al. 2005; Rahal et al. 2006; Seibert et al. 2011; Cappellari et al. 2014; Arias et al. 2015). This system consists of an extracorporeal frame and fixation elements – either pins or small-diameter wires – that stabilise the engaged bone segments that are connected with clamps to steel, aluminium or reinforced carbon-fibre connecting bars (Tyagi et al. 2014). These devices provide rigid skeletal fixa-

tion while permitting access to soft tissue injuries during fracture healing. The use of polymeric free-form connecting bars in external fixators has become widely used in veterinary orthopaedics (Okrasinski et al. 1991; Willer et al. 1991; Egger 1992; Roe and Keo 1997; Davis et al. 1998; De La Puerta et al. 2008).

This free-form type of fixation has the advantage that pin direction and diameter do not need to be influenced by the connecting bar location or by the clamp size, respectively (Roe and Keo 1997).

Poly(methyl methacrylate) (PMMA) is the most widely used polymer to be applied as a connecting bar (Preininger et al. 2012). This polymer has not only been used for these purposes, but also as hip implant cement (Gemmill et al. 2012; Roe et al. 2012; Song et al. 2013), for vertebral fixation and fusion (Sanders et al. 2004; Aikawa et al. 2013; Hettlich et al. 2013) and in maxillofacial surgery (Cook et al. 2001). This is due to the low cost of materials, the simplicity of the technique and its adaptability to a wide variety of pin diameters when compared with the clamp and rod device. An acrylic connecting bar can easily be contoured to the shape of the body and allows the surgeon to place trans-cortical pins in different planes (Shahar 2000; Alam et al. 2006). The PMMA hardens *in situ* through an exothermic polymerisation process, which takes about 10 minutes. This process can affect surrounding soft (Martinez et al. 1997) and hard tissue (Feith 1975; DiPisa et al. 1976; Li et al. 2003; Radev et al. 2009; Tyagi et al. 2014) by means of heat necrosis, when preventive actions are not taken.

Studies on PMMA made by Preininger showed that measurements of polymerisation temperature yielded maximum PMMA surface temperatures ranging from 101 °C to 110 °C and a two-minute-plateau of > 100 °C (Preininger et al. 2012). Previous studies exploring the fixation pin conductivity of heat from PMMA polymerisation have suggested a 1-cm safety margin to the tissue when the polymer is used as free-form ESF (Williams et al. 1997).

Previous studies have also reported deleterious effects on soft tissue with temperatures of 47 °C after one minute of exposure; one minute of 70 °C would have the same effect on bone tissue by means of denaturation of alkaline phosphatase (AP) enzyme (Matthews and Hirsch 1972; Rhinelander et al. 1979; Eriksson et al. 1982; Eriksson and Albrektsson 1983; Berman et al. 1984; Eriksson and Albrektsson 1984; Eriksson et al. 1984). Eriksson explored the minimum amount of heat needed to

produce bone damage using a thermal chamber for intravital microscopy of heated bone tissue. They showed that a temperature of only 50 °C for one minute is sufficient to produce bone tissue damage (Eriksson et al. 1982; Eriksson and Albrektsson 1983; Eriksson and Albrektsson 1984; Eriksson et al. 1984).

Epoxy putty (EPOX) has been compared to PMMA with respect to its biomechanical properties when used in free-form external skeletal fixation (Roe and Keo 1997; Goldberg et al. 2005; Tyagi et al. 2014). These studies showed a similar strength and greater apparent modulus of EPOX when compared with the PMMA (Roe and Keo 1997), making it a good alternative for free-form external fixation.

The purpose of this study was to determine the maximum heat of polymerisation generated by PMMA and EPOX and to assess biologically dangerous thermal transfer levels along stainless steel trans fixation pins of different diameters in a controlled *in vitro* environment.

MATERIAL AND METHODS

Study design. *In vitro* type I ESF were created using one 4.7 mm × 100 mm or a 2.7 mm × 100 mm trocar-pointed Steinmann intramedullary pin. These were placed perpendicularly to the bench and were suspended with a clamp holder fixed to a stand. Pieces of a tube were punctured in one wall such that the tip of the trocar-pointed pin reached the centre of the tube (Figure 1). These tubes were composed of anaesthesia aerosol hose (Hudson RCI®, Teleflex Medical, Research Triangle Park, USA) of 21 mm inner-diameter. Two different length of tubing filled with 33 cm³ and 17 cm³ of polymer as connecting bars, were used. Dental acrylic PMMA (Marche®, Santiago, Chile) and EPOX (POXILINA® 10 minutes, Akapol S.A., Buenos Aires, Argentina) were used and compared. The polymers were weighed and mixed as recommended by the manufacturer and used to fill the tubes of anaesthesia.

The temperature of the polymer was measured using a digital thermometer (Thermistor HI 93503, HANNA INSTRUMENTS, Woonsocket, USA) at the centre of the tube (Figure 1). The pin's temperature of dissipation during polymerisation was measured using *in situ* tele-thermographic measurements (Preininger et al. 2012) with an infrared
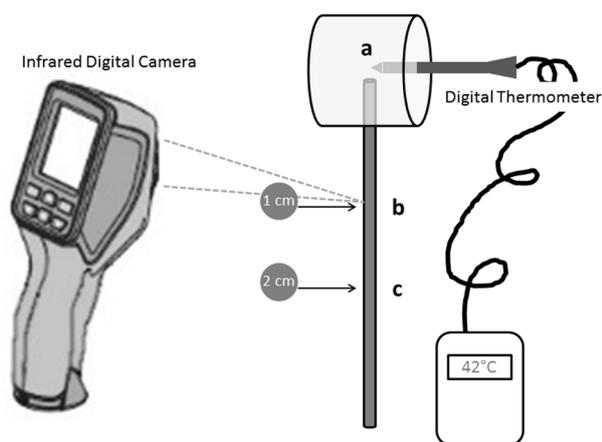
Figure 1. Basic diagram of the experimental thermal-measurement setup. An infrared digital camera was used to measure the thermal transfer to *in vitro* type I external skeletal fixators. Thermal measurement of polymerisation temperatures was performed in the middle of the polymers with a digital thermometer (a). Heat transfer measurement-point at 1 cm (b). Heat transfer measurement-point at 2 cm (c)

digital camera (FLUKE® VT02, Everett, USA) at 1 and 2 cm of the anaesthesia tube (Figure 1). This technology has been used to measure *in situ* polymerisation of PMMA *in vivo* and in *ex vivo* settings to measure differences in bone temperature generated during dental implant site preparation (Lucchiari et al. 2016). In this last publication, the accuracy of the temperature measurements recorded with the IR thermometer as well as that of the imaging and optical data was tested and contrasted by taking a series of measurements with a thermocouple (a method widely described in the literature) with a contact probe (FLUKE® 51, Everett, USA) inserted in the bone marrow. The authors concluded that IR imaging was a relatively inexpensive tool, easier to use and more accurate than a thermocouple. This technology has been recommended for the standardisation of experiments that measure bone temperatures (Mohlhenrich et al. 2015).

Resolution. The resolution of the infrared digital camera was 80 × 80 pixels, with a thermal sensitivity of < 0.1 °C (0.18 °F), field of view (FOV) of 17 ° × 17 °, minimum focus distance of 0.6 m (2 ft.), spatial resolution (IFOV) of 3.7 mrad and image frequency of 9 Hz; focus-free mode was used.

Detector data. The focal plane array (FPA) detector type was used with an uncooled microbolometer and a spectral range of 7.5–13 μm.

Measurements. Temperature measurement for this model of infrared camera ranges from −20 °C to +250°C (−4 °F to +482 °F), with an accuracy of ± 2 °C (± 3.6 °F) or ± 2% of reading. Background temperature was set in the menu of the VT02 to 24 °C and emissivity to 0.28 Ɛ, which corresponds to Type 316 polished surgical stainless steel at a temperature of 45 °C (75 °F). These parameters are given by the manufacturer as the emissivity values of common materials.

The camera was fix-mounted at 20 cm from the Steinmann intramedullary pin and the central-point aim-marker pointing to the desired measuring site. The PMMA and EPOX used in these experiments both hardened within 10 minutes. Thus, values where recorded every 30 seconds for each measurement point for a total time of 11 minutes. These measurements were taken for the two different quantities of PMMA and EPOX, with the two classes of Steinmann pins, in five repetitions each (Table 1).

Statistical analysis. For each treatment (polymer type, polymer quantity and tube diameter), five measurements were considered to represent the highest temperature interval (HTI). This interval was considered as the time when the maximum polymerisation temperatures (Tmax) was recorded, ± 30 s and ± 60 s. These measurements of HTI were performed at 1 cm and 2 cm from the polymer. Non-parametric Kruskal-Wallis ANOVA and *a posteriori* pair comparison tests were used to identify differences among treatments (Conover 1999).

RESULTS

Polymerisation temperatures

Tmax values in the centre of the polymer for PMMA and EPOX are showed in Table 2. A poten-

Table 1. Temperature measurements of poly(methyl methacrylate) and epoxy putty

Volume of polymer	Type of pins	Points of temperature measurement (cm)	Number of repetitions for each point
17 cm³	2.7 mm	0; 1 and 2	5
	4.7 mm	0; 1 and 2	5
33 cm³	2.7 mm	0; 1 and 2	5
	4.7 mm	0; 1 and 2	5

Table 2. Average highest temperature interval (HTI) in degrees Celsius (°C) for each experimental setup with epoxy putty (EPOX) and poly(methyl methacrylate) (PMMA), 1 cm from the polymer

Setup	Average HTI	SD
EPOX 4.7 × 17	31.7	0.94[a]
EPOX 2.7 × 33	31.7	0.94[a]
EPOX 2.7 × 17	28.3	1.62[a]
EPOX 4.7 × 33	37.6	2.62[c]
PMMA 2.7 × 17	46.4	8.07[d]
PMMA 4.7 × 33	49.6	7.53[d]
PMMA 4.7 × 17	48.8	6.75[d]
PMMA 2.7 × 33	47.0	5.58[d]

Different letters indicate significant differences between the mean results of the setups ($P < 0.05$)

tially dangerous level of heat transfer to soft tissue (temperatures over 47 °C) and hard tissue (temperatures over 50 °C) was observed with almost all the tested experimental setups. The Tmax of the PMMA measurements reached temperatures well over the 80 °C (Figure 2), while the EPOX did not reach 60 °C at the peak of the exothermic reaction of polymerisation (Figure 3).

Heat transfer from polymer to the pins

Significant differences were found in the HTI (H = 154.49, $P < 0.05$, and H = 153.94, $P < 0.05$; for measurements at 1 cm and 2 cm from polymer, respectively). For measurements taken at 1 cm from the polymer, all treatments with PMMA had significantly higher temperatures than those with EPOX. No differences were observed for all setups of PMMA, with average heat transfer temperatures being in the soft tissue damage range. All temperatures observed with EPOX were at least 10 °C lower than the soft tissue damage range. The lowest temperatures were obtained with the EPOX 4.7 mm × 17 cm³ setup (Table 2). For measurements performed at 2 cm from the polymer, the same pattern was observed, but with all HTI average temperatures well below the soft tissue damage range. All setups based on PMMA polymer had significant higher temperatures when compared
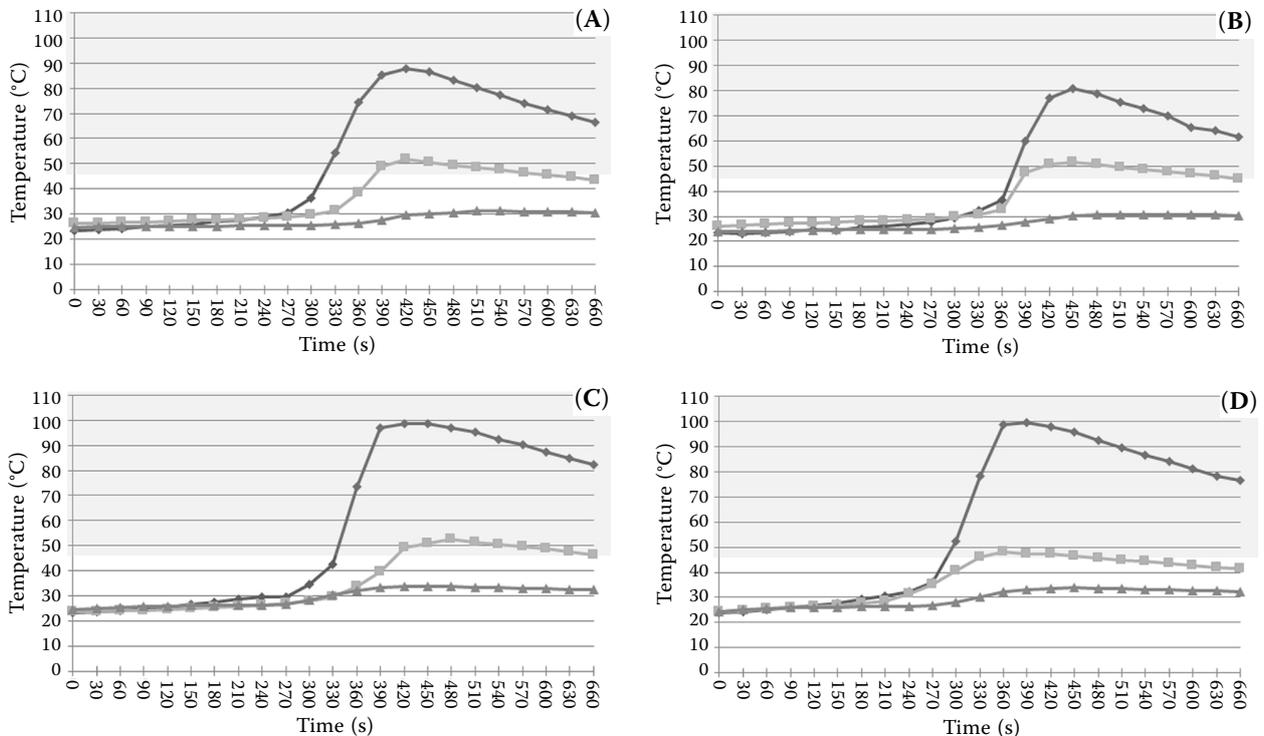

Figure 2. Mean measurements of poly(methyl methacrylate) polymer temperatures and heat transfer in the 11-minute polymerisation reaction. Graphs represent the 17 and 33 cm³ polymer volume setups with 2.7 and 4.7 mm Steinmann intramedullary pins. Lines show temperatures at the centre of the polymer (♦), 1 cm (■) and 2 cm (▲) from the Steinmann pin
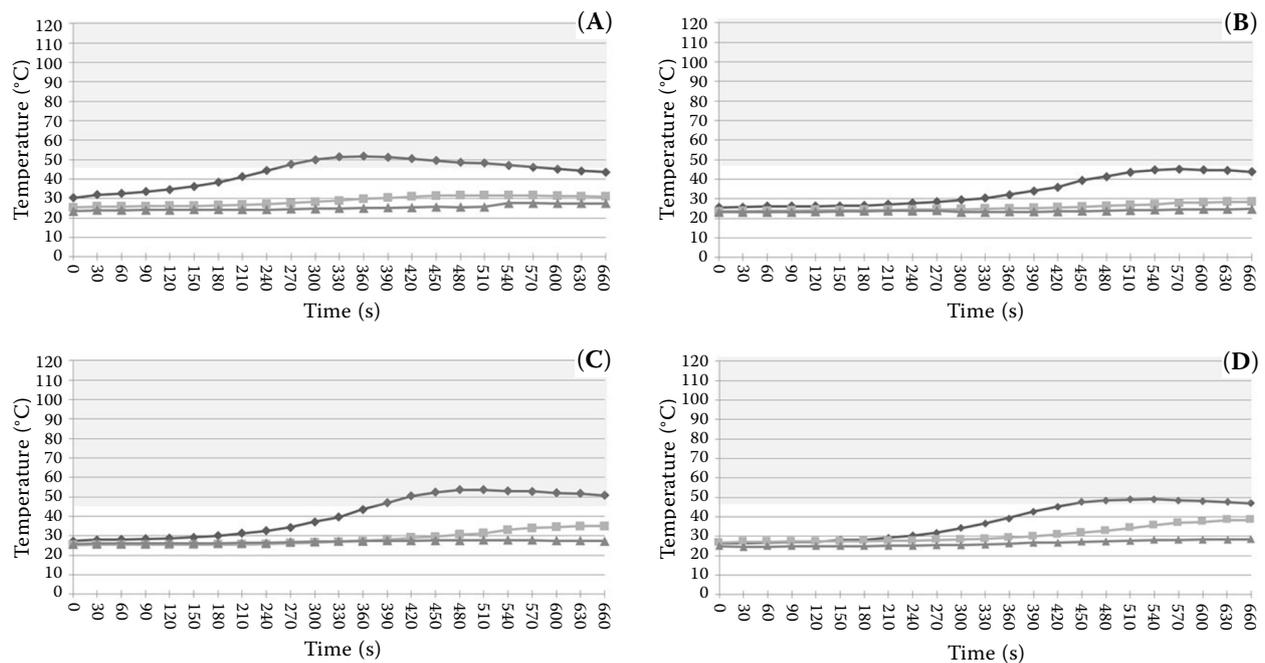
Figure 3. Mean measurements of epoxy polymer temperatures and heat transfer during the 11-minute polymerisation reaction. Graphs represent the 17 cm³ polymer volume setup with 2.7 mm Steinmann intramedullary pins (**A**), 17 cm³ polymer volume setup with 4.7 mm Steinmann intramedullary pins (**B**), 33 cm³ polymer volume setup with 2.7 Steinmann intramedullary pins (**C**) and 33 cm³ polymer volume setup with 4.7 mm Steinmann intramedullary pins (**D**). Lines show temperatures at the centre of the polymer (-◆-), 1 cm (-■-) and 2 cm (-▲-) from the Steinmann pin

to EPOX setups, and PMMA 4.7 mm × 33 cm³ and 2.7 mm × 33 cm³ showed the highest temperatures. The lowest temperature, meanwhile, was recorded with EPOX 4.7 mm × 17 cm³ (Table 3).

DISCUSSION

The EPOX results show that the heat transfer from the polymerising putty to the pins did not reach 47 °C at any time and with any of the experimental setups tested (Figure 3), regardless of the amount of EPOX or the diameter of the pin used. This means that both bone and nerve tissue would not undergo irreversible injury and cell death, because they would not be exposed to temperatures over 47 °C for 1 to 2 minutes, as described by Goldberg (Goldberg et al. 2005) and others before him (Matthews and Hirsch 1972; Xu and Pollock 1994).

The PMMA results demonstrate that, at 1 cm from the polymer, in all of the tested experimental setups a temperature of 47 °C was reached and maintained for more than 1 min. However, only three of the four experimental conditions (both

of the 17 cm³ polymer volumes and the 33 cm³ with 2.7 mm pin) reached a temperature of 50 °C for more than 1 min. This has been described as the minimal condition necessary for bone damage to occur (Eriksson and Albrektsson 1983; Eriksson and Albrektsson 1984; Eriksson et al. 1984) (Figure 2). This differs from the recom-

Table 3. Average highest temperature interval (HTI) in degrees Celsius (°C) for each experimental setup with epoxy putty (EPOX) and poly(methyl methacrylate) (PMMA), 2 cm from the polymer

Setup	Average HTI	SD
EPOX 4.7 × 17	27.5	0.65[a]
EPOX 2.7 × 33	27.5	0.65[b]
EPOX 2.7 × 17	25.1	1.66[b]
EPOX 4.7 × 33	28.6	2.47[b]
PMMA 4.7 × 17	31.1	1.62[c]
PMMA 2.7 × 17	33.5	1.21[c]
PMMA 4.7 × 33	30.7	0.73[d]
PMMA 2.7 × 33	33.5	1.34[d]

Different letters indicate significant differences between the mean results of the setups (*P* < 0.05)

mendations given by Martinez et al. (1997) and Williams et al. (1997), who proposed the 10 mm mark as the safety limit.

On the other hand, *in vitro* PMMA transfer at 2 cm from the polymer resulted in safe temperatures, far lower than the 47 °C level necessary for tissue damage. In the literature, temperature increases elicited by the drilling of bone as well as K-wire and Steinmann pin insertion are associated with far higher temperatures (Pandey and Panda 2013). Elevation of temperature through this mechanism is much more likely to cause tissue damage and implant loosening (Matthews and Hirsch 1972; Berman et al. 1984; Lucchiari et al. 2016).

In conclusion, epoxy putty is a versatile, inexpensive and safe polymer that is suitable for use in free-form external skeletal fixation, because the exothermic polymerisation process does not transfer enough heat to the fixation pins to affect soft or hard tissue at 1 cm from the polymer.

PMMA, on the other hand, exhibits polymerisation temperatures that are higher than those of Epoxy. The transfer of heat to the pins is also higher. Nonetheless, this thermal transfer is only dangerous when soft or hard tissue is in contact with the fixation pins at less than 2 cm from the polymer.

Based on the results of this study, distances of at least 1 cm from the EPOX polymer and at least 2 cm from the PMMA polymer are recommended.

Finally, it seems highly unlikely that the transfer of heat from the polymerisation of both EPOX and PMMA through the trans fixation pins would elicit bone necrosis and implant loosening, since they are fastened to the bone at distances that normally exceed 2 cm from the polymer.

REFERENCES

Aikawa T, Shibata M, Fujita H (2013): Modified ventral stabilization using positively threaded profile pins and polymethylmethacrylate for atlantoaxial instability in 49 dogs. Veterinary Surgery 42, 683–692.

Alam MR, Heo SY, Lee HB, Kim JH, Park YJ, Lee KC, Choi IH, Kim NS (2006): Preaxial longitudinal intercalary radial hemimelia in a dog: a case report. Veterinarni Medicina 51, 118–123.

Arias JI, Beato C, Espinoza A (2015): Epoxy putty external skeletal fixation in a tibiotarsal fracture of a wild choroy parakeet (Enicognathus leptorhynchus). Arquivo Brasileiro de Medicina Veterinaria e Zootecnia 67, 671–678.

Berman AT, Reid JS, Yanicko Jr DR, Sih GC, Zimmerman MR (1984): Thermally induced bone necrosis in rabbits. Relation to implant failure in humans. Clinical Orthopaedics and Related Research 284–292.

Cappellari F, Piras L, Panichi E, Ferretti A, Peirone B (2014): Treatment of antebrachial and crural septic nonunion fractures in dogs using circular external skeletal fixation: a retrospective study. Veterinary and Comparative Orthopaedics and Traumatology 27, 297–305.

Conover WJ (1999): Practical Nonparametric Statistics. John Wiley and Sons, New York. pp 584.

Cook WT, Smith MM, Markel MD, Grant JW (2001): Influence of an interdental full pin on stability of an acrylic external fixator for rostral mandibular fractures in dogs. American Journal of Veterinary Research 62, 576–580.

Davis M, Schulz KS, Fawcett A, Slater MR, Roths JB (1998): Flexural and torsional analysis of five acrylics for use in external skeletal fixation. Veterinary and Comparative Orthopaedics and Traumatology 11, 53–58.

De La Puerta B, Emmerson T, Moores AP, Pead MJ (2008): Epoxy putty external skeletal fixation for fractures of the four main metacarpal and metatarsal bones in cats and dogs. Veterinary and Comparative Orthopaedics and Traumatology 21, 451–456.

DiPisa JA, Sih GS, Berman AT (1976): The temperature problem at the bone-acrylic cement interface of the total hip replacement. Clinical Orthopaedics and Related Research 121, 95–98.

Egger EL (1992): Instrumentation for external fixation. Veterinary Clinics of North America. Small Animal Practice 22, 19–43.

Eriksson AR, Albrektsson T (1983): Temperature threshold levels for heat-induced bone tissue injury: a vital-microscopic study in the rabbit. Journal of Prosthetic Dentistry 50, 101–107.

Eriksson RA, Albrektsson T (1984): The effect of heat on bone regeneration – an experimental study in the rabbit using the bone-growth chamber. Journal of Oral and Maxillofacial Surgery 42, 705–711.

Eriksson A, Albrektsson T, Grane B, McQueen D (1982): Thermal injury to bone. A vital-microscopic description of heat effects. International Journal of Oral Surgery 11, 115–121.

Eriksson RA, Albrektsson T, Magnusson B (1984): Assessment of bone viability after heat trauma. A histological, histochemical and vital microscopic study in the rabbit. Scandinavian Journal of Plastic and Reconstructive Surgery and Hand Surgery 18, 261–268.

Feith R (1975): Side-effects of acrylic cement implanted into bone. A histological, (micro)angiographic, fluorescence-microscopic and autoradiographic study in the

rabbit femur. Acta Orthopaedica Scandinavica, Supplementum 161, 3–136.

Gemmill TJ, Pink J, Clarke SP, McKee WM (2012): Total hip replacement for the treatment of atraumatic slipped femoral capital epiphysis in dogs. The Journal of Small Animal Practice 53, 453–458.

Goldberg SH, Cohen MS, Young M, Bradnock B (2005): Thermal tissue damage caused by ultrasonic cement removal from the humerus. The Journal of Bone and Joint Surgery 87, 583–591.

Hettlich BF, Allen MJ, Pascetta D, Fosgate GT, Litsky AS (2013): Biomechanical comparison between bicortical pin and monocortical screw/polymethylmethacrylate constructs in the cadaveric canine cervical vertebral column. Veterinary Surgery 42, 693–700.

Li C, Kotha S, Mason J (2003): Evaluation of the effects of implant materials and designs on thermal necrosis of bone in cemented hip arthroplasty. Bio-Medical Materials and Engineering 13, 419–428.

Lucchiari N, Frigo AC, Stellini E, Coppe M, Berengo M, Bacci C (2016): In vitro assessment with the infrared thermometer of temperature differences generated during implant site preparation: The traditional technique versus the single-drill technique. Clinical Implant Dentistry and Related Research 18, 182–191.

Martinez SA, Arnoczky SP, Flo GL, Brinker WO (1997): Dissipation of heat during polymerization of acrylics used for external skeletal fixator connecting bars. Veterinary Surgery 26, 290–294.

Matthews LS, Hirsch C (1972): Temperatures measured in human cortical bone when drilling. Journal of Bone and Joint Surgery. American Volume 54, 297–308.

Mohlhenrich SC, Modabber A, Steiner T, Mitchell DA, Holzle F (2015): Heat generation and drill wear during dental implant site preparation: systematic review. British Journal of Oral and Maxillofacial Surgery 53, 679–689.

Okrasinski EB, Pardo AD, Graehler RA (1991): Biomechanical evaluation of acrylic external skeletal fixation in dogs and cats. Journal of the American Veterinary Medical Association 199, 1590–1593.

Ozsoy S, Altunatmaz K (2003): Treatment of extremity fractures in dogs using external fixators with closed reduction and limited open approach. Veterinarni Medicina 48, 133–140.

Pandey RK, Panda SS (2013): Drilling of bone: A comprehensive review. Journal of Clinical Orthopaedics and Trauma 4, 15–30.

Preininger B, Matziolis G, Pfitzner T, Hardt S, Perka C, Rohner E (2012): In situ tele-thermographic measurements during PMMA spacer augmentation in temporary arthrodesis after periprosthetic knee joint infection. Technology and Health Care 20, 337–341.

Radev BR, Kase JA, Askew MJ, Weiner SD (2009): Potential for thermal damage to articular cartilage by PMMA reconstruction of a bone cavity following tumor excision: A finite element study. Journal of Biomechanics 42, 1120–1126.

Rahal SC, Volpi RS, Hette K, Teixeira Neto FJ, Vulcano LC (2006): Arthrodesis tarsocrural or tarsometatarsal in 2 dogs using circular external skeletal fixator. Canadian Veterinary Journal 47, 894–898.

Rhinelander FW, Nelson CL, Stewart RD, Stewart CL (1979): Experimental reaming of the proximal femur and acrylic cement implantation: vascular and histologic effects. Clinical Orthopaedics and Related Research 141, 74–89.

Roe SC (2005): External fixators, pins, nails, and wires. In: Johnson AL, Houlton JEF, Vannini R (eds): AO Principles of Fracture Management in the Dog and Cat. AO Thieme Medical Publications, New York. 52–72.

Roe SC, Keo T (1997): Epoxy putty for free-form external skeletal fixators. Veterinary Surgery 26, 472–477.

Roe S, Marcellin-Little D, Lascelles BD (2012): Radiographic evaluation of early periprosthetic femoral bone contrast and prosthetic stem alignment after uncemented and cemented total hip replacement in dogs. Veterinary Surgery 41, 902–903; author reply 903–904.

Sanders SG, Bagley RS, Silver GM, Moore M, Tucker RL (2004): Outcomes and complications associated with ventral screws, pins, and polymethyl methacrylate for atlantoaxial instability in 12 dogs. Journal of the American Animal Hospital Association 40, 204–210.

Seibert RL, Lewis DD, Coomer AR, Sereda CW, Royals SR, Leasure CS (2011): Stabilisation of metacarpal or metatarsal fractures in three dogs, using circular external skeletal fixation. New Zealand Veterinary Journal 59, 96–103.

Shahar R (2000): Relative stiffness and stress of type I and type II external fixators: Acrylic versus stainless-steel connecting bars A Theoretical Approach. Veterinary Surgery 29, 59–69.

Song J, Sheehy JG, Dyce J (2013): En-bloc femoral cement removal after failure of cemented total hip replacement in two dogs. Veterinary and Comparative Orthopaedics and Traumatology 26, 130–134.

Theyse LF, Voorhout G, Hazewinkel HA (2005): Prognostic factors in treating antebrachial growth deformities with a lengthening procedure using a circular external skeletal fixation system in dogs. Veterinary Surgery 34, 424–435.

Tyagi SK, Aithal HP, Kinjavdekar P, Pawde AM, Srivastava T, Tyagi KP, Monsang SW (2014): Comparative evaluation

of in vitro mechanical properties of different designs of epoxy-pin external skeletal fixation systems. Veterinary Surgery 43, 355–360.

Willer RL, Egger EL, Histand MB (1991): Comparison of stainless steel versus acrylic for the connecting bar of external skeletal fixators. Journal of the American Animal Hospital Association 27, 541–548.

Williams N, Tomlinson JL, Hahn AW, Constantinescu GM, Wagner-Mann C (1997): Heat conduction of fixator pins with polymethylmethacrylate external fixation. Veterinary and Comparative Orthopaedics and Traumatology 3, 37–43.

Xu D, Pollock M (1994): Experimental nerve thermal injury. Brain 117, 375–384.