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PAPER

A humeral intracondylar repair system for the management of humeral intracondylar fissure and humeral condylar fracture

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Objectives: To report complications, clinical outcomes and CT-imaging outcomes of a surgical system designed for the management of humeral intracondylar fissures and humeral condylar fractures.

Materials and Methods: Retrospective review of fracture healing from medical records, direct owner contact and an online data-submission service. Follow-up included CT scans and a calculated "bone-opacity continuity index" to quantify bone healing.

Results: There was one major surgical complication and one major medical complication out of 34 fissure cases, and two major surgical and one major medical complication out of 14 fractures. Follow-up times ranged from 29 to 1268 days. All cases with CT follow-up had some continuity of bone opacity across the condyle.

Clinical Significance: In the cases included in this study, this repair system was associated with low complication rates and favourable healing rates, particularly for humeral intracondylar fissure.

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INTRODUCTION

Humeral intracondylar fissure, also referred to as incomplete ossification of the humeral condyle (IOHC) and incomplete humeral condylar fracture, has been identified in several breeds (Marcellin-Little *et al.* 1994, Butterworth & Innes 2001, Robin & Marcellin-Little 2001, Moores 2006, Hattersley *et al.* 2011), but spaniel breeds are over-represented. American cocker spaniels are reportedly most commonly affected in the USA (Marcellin-Little *et al.* 1994), German wachtels appear in publications from Germany (Meyer-Lindenberg *et al.* 2002) and English springer spaniels are the most commonly treated breed in the UK (Moores 2006). CT screening identified a prevalence of 14% in non-lame English springer spaniels that were sedated or anaesthetised for reasons other than thoracic limb lameness (Moores *et al.* 2012).

Spaniel breeds have been recognised as being pre-disposed to humeral condylar fracture (Glyde *et al.* 2003, Moores 2006), and current understanding is that pre-existing humeral intracondylar fissure is an underlying factor in some of these patients. Clinical follow-up on sound English springer spaniels diagnosed with non-clinical humeral intracondylar fissures revealed that approximately 18% of these cases progressed to fracture, and a total of approximately 24% required surgical management within the follow-up period (Moores & Moores 2017).

An initial hypothesis on the aetiology of humeral intracondylar fissure was that it was a failure of the two humeral condylar ossification centres to fuse (Marcellin-Little *et al.* 1994). However, at least three cases have been reported in which either a *de novo* fissure has formed, or a partial fissure has propagated to complete fissure, in an interval between two episodes of cross-sectional imaging (Witte *et al.* 2010, Farrell *et al.* 2011, Piola *et al.* 2012). Furthermore, histologic analysis has repeatedly failed to demonstrate persistent cartilage at the fissure site, and has been more consistent with fibrous non-union (Marcellin-Little *et al.* 1994, Gnudi *et al.* 2005, von Pfeil *et al.* 2010). CT and MRI findings include, as well as the fissure, areas of bone sclerosis either side of the fissure (Carrera *et al.* 2008, Piola *et al.* 2012).

Another hypothesis is that humeral intracondylar fissure is a stress fracture (Butterworth & Innes 2001, Farrell *et al.* 2011), although few arguments have been proposed for the underlying cause of stress fracture, or whether it is an insufficiency fracture due to compromised bone health, or a fatigue fracture through repetitive, abnormal loads.

Clinical outcomes for the surgical management of humeral intracondylar fissure, and of humeral condylar fractures, have generally been reasonable in case reports and single-centre case series (Butterworth & Innes 2001, Robin & Marcellin-Little 2001, Meyer-Lindenberg *et al.* 2002, Moores *et al.* 2014). However, high complication rates have been reported in multicentre retrospective case series on both humeral intracondylar fissure (Hattersley *et al.* 2011) and humeral condylar fractures (Perry *et al.* 2015). In particular, surgical site infection and seroma formation have been frequently reported (Hattersley *et al.* 2011). Fissure healing rates, based on various imaging modalities, have been inconsistent, with some authors reporting low rates of healing (Butterworth & Innes 2001) and others reporting more positive results (Meyer-Lindenberg *et al.* 2002, Fitzpatrick *et al.* 2009). Papers on techniques based on screw placement using a traditional approach to articular fracture management, namely accurate reduction and rigid internal fixation, have reported implant fatigue failure at variable time periods after surgical intervention suggesting that a failure of fracture healing and a reliance on the implant for long-term stability can lead to late complications (Charles *et al.* 2009)

This article outlines the clinical results of the preliminary use of a custom-designed, self-compressing screw, used in combination with bone allograft or autograft, for the management of humeral intracondylar fissure and humeral condylar fracture. The data that was used to develop this new implant will be the subject of a future publication.

METHOD

Surgery

The humeral intracondylar repair system (HIRS) comprises a headless, self-compressing screw and a stepped drill bit (Fig 1). A 2 mm pilot hole is drilled across the humeral condyle and measured for depth. The stepped drill bit has a leading, smooth 1.9 mm diameter section that follows the pilot hole, a narrow (3.1 mm) fluted section that drills the section of the hole for the trans thread of the screw, a wide (5.9 mm) fluted section that drills the central void and the thread hole for the cis thread of the screw and three laser marks that facilitate drilling to a specific depth. Once drilled, the stepped hole is cleared and flushed, and the HIRS screw is inserted. The self-tapping trans thread is engaged by partially advancing the screw. The drill bit creates a 5.9 mm diameter void around the 3 mm diameter central section of the screw, at the level of the fissure, removing sclerotic bone either side of the fissure and allowing the void to be packed with demineralised bone matrix (DBM) in a calcium phosphate nanopaste, if available, or autogenous cancellous bone graft or other form of DBM, if not. The screw is then fully advanced until tight, generating compression at the fissure/fracture via the variable pitches of the cis and trans threads.

FIG 1. The Humeral Intracondylar Repair System (HIRS) drill bit and implant

Various methods were used to position and direct the pilot hole, including CT-assisted planning, use of an aiming device, fluoroscopic guidance and free-hand aiming, according to surgeon preference. For condylar fractures, pilot holes were either drilled "outside-in," or were started "inside-out" and completed in the opposite direction after fracture reduction (Denny 2006). The HIRS screw is designed to be placed medial-to-lateral in cases of humeral intracondylar fissure, and was placed in this manner in all cases but one. For fractures, the direction depended on the fracture configuration, and, in this series, the HIRS screw was placed in a lateral-to-medial direction in all lateral condylar fractures (LCF). All fractures were treated using the HIRS in combination with bone plates of various designs.

Peri-operative antibiotic therapy was provided in all cases treated at the primary centre, with most receiving cefuroxime 20 mg/kg intravenous (iv), at least 30 minutes prior to first incision and every 90 minutes until recovery from anaesthesia. For cases treated at other centres, details of peri-operative anti-biotic use were not provided. Post-operative antibiotics were prescribed at the surgeon's discretion.

Data collection

Data were collected for three groups of cases: humeral intracondylar fissure cases operated at the primary centre (May 2014 to October 2017), humeral condylar fractures operated at the primary centre for the same time period, and humeral intracondylar fissure cases operated at multiple other sites (February 2017 to July 2018). During the study period, the HIRS was only used on fractures believed to be secondary to humeral intracondylar fissures, and not on humeral condylar fractures that were believed to be due to acute trauma only. Clinical and surgical findings that were considered suggestive of preceding fissures included fracture occurrence during normal activity with no trauma, prodromal lameness, humeral intracondylar fissure in the contralateral limb and/ or sclerosis at the intracondylar fracture surface at the time of surgery. Surgeries were defined as "primary" if the HIRS was used during the first surgery on that fissure or fracture, and as "revision" if the HIRS was used in a humerus that had received previous surgery for the same condition. Given the different methods of data collection, the two groups of humeral intracondylar fissure cases are summarised separately, and as a pooled group.

Clinical outcomes

Patients undergoing a HIRS procedure were logged and clinical details were recovered retrospectively from the hospital database. Owners were invited to return with their dogs for clinical examination and/or diagnostic imaging. Owners who declined this invitation were offered assessment and/or diagnostic imaging at their local veterinary practice, and/or completed a telephone questionnaire. Owners were asked to complete Liverpool Osteoarthritis in Dogs (LOAD) instruments (Walton *et al*. 2013, Muller *et al*. 2016) at various stages of recovery, and at final follow-up. Owners were also asked to categorise the overall functional outcome as "normal," "acceptable" or "poor." On clinical examination, lameness was scored by the veterinarian on a 6-point numerical rating scale (0, *no lameness*, to 5, *non-weight bearing*).

For cases operated at sites other than the primary centre, data were submitted by the operating surgeons, all of whom are co-authors, via a web-based data entry portal (JotForm, San Francisco, CA). All cases in which the HIRS was used during the study period were included. Follow-up time was recorded in intervals as 29-42 days, 42-84 days, 3–6 months and greater than 6 months.

Complications

Complications were defined as "minor" if no specific treatment was required and there was no adverse effect on outcome, and as "major" if specific treatment was required and/or there was an adverse effect on long-term outcome (Cook *et al*. 2010). Major complications were sub-classified as "major-medical" or "major-surgical," based on what further treatment was required.

Imaging follow-up

For cases with CT follow-up, quantitative measurements were made: for each slice of the native (unreconstructed) CT scan, linear measurements were made, using medical imaging software (Osirix, Pixmeo SARL, Geneva), of what appeared to be "bone" (based on opacity and pattern), persistent "fissure" (based on a linear interruption of bone opacity or pattern), persistent "void" around the implant and "implant/ artefact," as well as the total "length" of the cross-section at that slice, along the plane of the fissure, if present (Fig 2). The values from each native slice of the CT scan for each of these measurements were summed, giving a surrogate measure of the total cross-sectional area occupied. Finally, the values for each measurement were divided by the

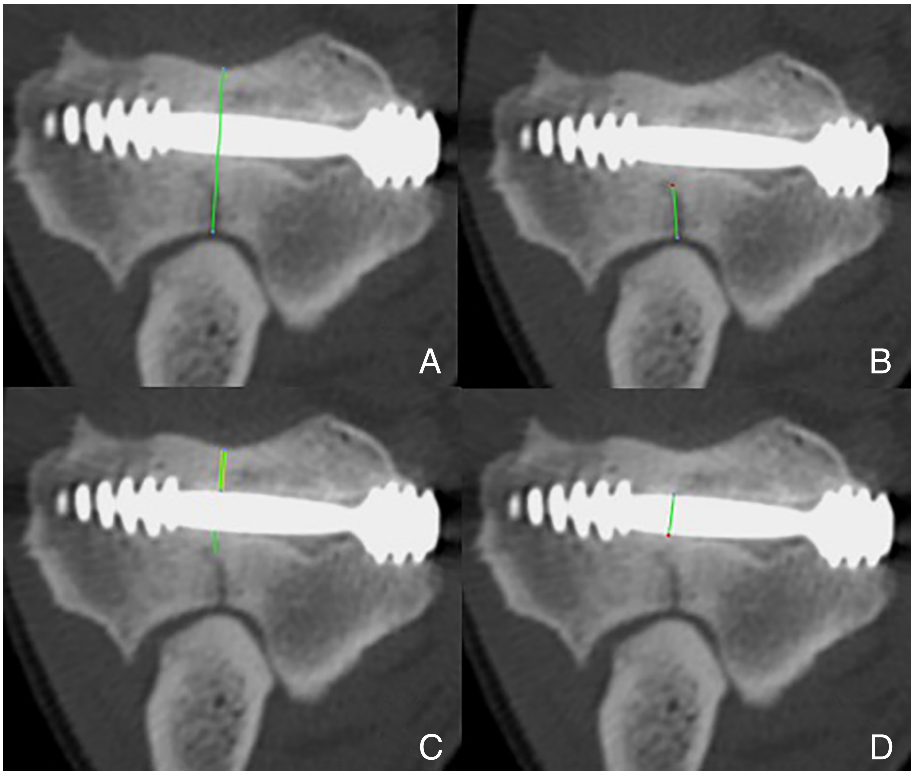

FIG 2. The measurement of total bone width (A), fissure length (B), bone-opacity continuity (C) and implant/artefact (D) on operative and follow-up CT scans. These measurements were repeated for each native slice of the scans

value for total length and multiplied by one hundred, thereby giving an estimate of each as a percentage of total cross-sectional area. This technique was repeated by two observers (MBW and EC). Inter-observer agreement was tested using intra-class correlation coefficient (ICC).

Statistical analysis

A "bone-opacity continuity index" was calculated for each case, where the percentage cross-sectional area values were used in the following formula:

$$\text{Bone} - \text{opacity Continuity Index}\ (\%) = \left[(\text{Bone})/(\text{Bone}+\text{Void}+\text{Fissure})\right]\times 100$$

This statistic gives an indication of the degree of bone-opacity continuity that ignores the screw/artefact percentage cross-sectional area, minimising the effect of humeral condylar diameter on estimates of healing. A bone-opacity continuity index of 100% would reflect complete bone-opacity continuity across the humeral condyle, and a bone-opacity continuity index of 0% would reflect a complete persistent fissure/fracture.

Data were scatter-plotted and assessed subjectively for associations between age and bone-opacity continuity index, and between follow-up interval (time from surgery to imaging) and bone-opacity continuity index.

Humeral intracondylar fissure cases and humeral fracture cases with CT follow-up were compared for age and bone-opacity continuity index using Student's *t* test, and for follow-up interval using a Mann-Whitney U test.

RESULTS

Cases

Signalments of the groups are summarised in Table 1. One of 19 humeral intracondylar fissure cases at the primary centre, and one of 20 humeral intracondylar fissure cases at the other centres were revision surgeries. All humeral fissure cases were complete fissures. Of the 14 fracture cases at the primary centre, eight were primary LCF, one was a primary medial condylar fracture, four were revision LCF and one was a revision dicondylar fracture.

All dogs treated at the primary centre received peri-operative antibiotic treatment according to the protocol. Four dogs did not receive post-operative antibiotics (one fissure, three fractures), 27 dogs received cephalexin (16 fissures, 11 fractures) and two dogs received amoxicillin-clavulanate (two fissures) for an average of 9 days. The HIRS screw was placed in a medial to lateral direction in 18 fissure cases and lateral to medial in one. For fractures, the HIRS screw was placed lateral to medial with an inside-out technique in nine cases and an outside-in technique in three cases, and in a medial to lateral direction using an inside-out technique in two cases (one medial condylar fracture and one revision dicondylar fracture). The peri-implant void was packed with DBM granules in 14 cases, DBM in calcium phosphate nanopaste in 11, an unknown preparation of DBM in three and autogenous cancellous bone graft in two cases. The void was not packed in two cases and, in one, the use of bone graft or substitute was not recorded.

In the multi-centre cases, all HIRS implants were placed in a medial to lateral direction, and the void was packed with DBM in calcium phosphate nanopaste in 12 cases, autogenous cancellous bone graft in seven and was not packed in one.

From the primary centre, one humeral intracondylar fissure case was lost to follow-up, and only telephone follow-up was available for one fracture.

Clinical outcomes

LOAD scores at presentation were available for six humeral intracondylar fissure cases treated at the primary centre. Mean and median LOAD scores for these cases were 16 and 12, respectively (range 11 to 26, where higher scores indicate a greater level of owner-assessed disability, and a range of 0 to 52 is theoretically possible).

For cases operated at the primary centre, the mean and median times to final follow-up were 649 and 733 days, respectively (range 118 to 1268 days). LOAD score was available for 11 dogs treated for humeral intracondylar fissure, with a median of 4 (range 1-22), and for seven dogs treated for humeral condylar fracture, with a median of 4 (range 0-32). Overall owner

Table 1. Signalment data of cases

	Primary centre HIF cases	Multi-centre HIF cases	Primary centre fracture cases
Number of procedures	19	20	14
Number of dogs	17	16	14[*]
Breeds	12 ESS	11 ESS	12 ESS
	2 ESS ×	2 ESS × cocker	1 cocker spaniel
	1 cocker spaniel	1 cocker spaniel	1 Clumber spaniel
	1 Labrador	1 Border Collie	
	1 Cross breed	1 golden retriever × poodle	
Gender/Neuter status	10 Male entire	9 Male entire	5 Male entire
	6 Male neutered	1 Male neutered	4 Male neutered
	1 Female entire	2 Female entire	5 Female neutered
	2 Female neutered	4 Female neutered	
Age (days, mean±sd)	1468±829	967±935	2156±1334
Bodyweight (kg, mean±sd)	20.6±3.46	20.1±2.4	21.1±3.46

ESS English springer spaniel, × = cross, HIF humeral intracondylar fissure
[*]Two dogs with condylar fractures had the contralateral limb treated for HIF, and are therefore included in both columns

satisfaction scores were available for 12 dogs treated for humeral intracondylar fissure: 10 dogs were scored "normal" and two were scored "acceptable." The same scores were available for nine dogs treated for humeral condylar fracture: seven were scored "normal" and two were scored "acceptable." Veterinary assessment of lameness was available for 10 dogs treated for humeral intracondylar fissure and was 0 of 5 in all 10. The same assessment was available for eight cases treated for humeral condylar fracture and was zero of five in seven, and one of five in one (a revision of a dicondylar fracture).

For multi-centre cases, follow-up was available for 16 cases. Follow-up time was between 29 and 42 days for one case, between 43 and 84 days for 10 cases and between 3 and 6 months for five cases. Veterinary-assessed lameness scores were available for 16 cases: 0 of 5 in 14 cases and 1 of 5 in two.

Complications

Complications are summarised in Table 2.

There was one major surgical complication – implant loosening – when the HIRS was used in primary humeral intracondylar fissure procedures. The radiographic position of this screw was too proximal, thereby resulting in reduced bone purchase.

There were two major surgical complications when the HIRS was used to treat primary condylar fractures. One dog suffered screw loosening and surgical site infection associated with the dynamic compression plate on the lateral epicondyloid ridge. This plate was removed and replaced with a locking plate, the HIRS implant was tightened and remained in situ. The explanted screws were submitted for bacteriology: a coagulase-positive *Staphylococcus* was isolated and a 6-week course of amoxicillin-clavulanate was prescribed. There was no recurrence of clinical signs and the dog had an excellent long-term outcome. In one dog, a plate screw fractured and was replaced. The same dog subsequently developed surgical site infection and did not present until the owner was contacted regarding clinical follow-up for this study. All implants were removed and submitted for bacteriology: methicillin-resistant *Staphylococcus aureus*, sensitive to trimethoprim-sulphonamide, was isolated, and an 8-week course of this antibiotic was prescribed. This dog had an "acceptable" clinical outcome, according to owner assessment.

Imaging follow-up

CT follow-up was available for 17 elbows: 11 complete fissures and 6 fractures, at mean and median follow-up times of 453 and 461 days, respectively (range 64 to 1033 days). ICC for inter-observer agreement was 0.88–0.91 for most values, and 0.2 for "screw-artefact" (Table 3). All cases demonstrated some bone-opacity continuity across the condyle (Fig 3). Mean (±sd) bone-opacity continuity index was 67±28% for humeral intracondylar fissure, and 73±19% for humeral condylar fracture. Median bone-opacity continuity index was 64% for humeral intracondylar fissure (range 14-100%, interquartile range 49-90%) and 68% for

Table 2. Complications

	Primary centre HIF cases	Multi-centre HIF cases	Combined HIF cases	Primary centre fracture cases
Number of procedures	19	20	39	14
Number of dogs	17	16	33	14[*]
Intra-operative complications	0	2/20 (10%)[†]	2/39 (5%)	0
Number of cases lost to follow-up	1	4	5	0 (one dog phone follow-up only)
Number of dogs lost to follow-up	1	3	4	0
Post-operative complications				
Minor	2/18 (11%)[‡]	1/16 (6%)[§]	3/34 (9%)	1/14 (7%)[¶]
Major medical	0	1/16 (6%)[**]	1/34 (3%)	1/14 (7%)[††]
Major surgical	1/18 (6%)[‡‡]	0	1/34 (3%)	2/14 (14%)[§§]
Total major	1/18 (6%)	1/16 (6%)	2/34 (6%)	3/14 (21%)
Total post-operative complications	3/18 (17%)	2/16 (12.5%)	5/34 (15%)	4/14 (29%)

HIF humeral intracondylar fissure
*Two dogs with condylar fractures had the contralateral limb treated for HIF, and are therefore included in both columns
†One drill bit broke, one drill bit was blunt
‡Two cases developed seromas
§One case developed a synoviocoele
¶One case of radial neuropraxia
**One surgical site infection
††One case of surgical site infection that responded to medical management
‡‡One implant loosened
§§Two cases of surgical site infection requiring surgical management

Table 3. Quantitative imaging follow-up

	Fissure	Bone	Void	Screw/Artefact
Inter-observer ICC	0.9	0.91	0.88	0.20
Mean	27.7%	60.3%	2.16%	9.16%
sd	22.5%	21.5%	3.53%	2.49%
Min	0.00%	13.0%	0.00%	7.00%
Median	24.5%	58.0%	0.00%	8.50%
Max	76.0%	88.0%	9.50%	17.0%

ICC = intra-class correlation coefficient
All figures are a percentage of total cross-sectional area

humeral condylar fracture (range 51-97%, interquartile range 61-89%).

There was no difference between fissure cases and fracture cases for age (P = 0.149, Student's *t* test), follow-up interval (P = 0.962, Mann-Whitney U) or bone-opacity continuity index (P = 0.6, Student's *t* test).

Based on subjective assessment of scatterplots, there was no apparent association between age and bone-opacity continuity index (Fig 4), or between follow-up interval and bone-opacity continuity index (Fig 5).

DISCUSSION

The HIRS was designed to optimise bone healing and minimise complications in the surgical management of humeral intracondylar fissure and humeral condylar fracture. In order to optimise bone healing, the aims in its design were to achieve excellent stability through fissure compression and bone-holding on both sides of the fissure, and to provide access for bone graft delivery to the fissure. In order to try to minimise the risks of complications, a headless design was used to minimise soft-tissue irritation, a self-compressing design was used to create compression of the fissure/fracture, a medial-to-lateral insertion method was advised as the standard operating procedure and factors contributing to implant fatigue failure were considered. Furthermore, method of hole preparation was considered with the aims of simplifying the surgical procedure, minimising the risk of joint surface compromise and allowing cost-effective instrumentation manufacture.

One proposed aetiopathogenesis of humeral intracondylar fissure is that it is a form of non-healing stress fracture, based on documented *de novo* formation and propagation in adult dogs (Witte *et al.* 2010, Farrell *et al.* 2011, Piola *et al.* 2012), and histopathology (Gnudi *et al.* 2005, Fitzpatrick *et al.* 2009). Accordingly, the HIRS was designed based on the principles of managing fractures in challenging healing environments and non-union fractures, namely: stable fixation with compression, and bone grafting. The isthmus of the humeral condyle is logically a biologically disadvantaged region of bone, being mostly isolated within the synovial space of the elbow joint, mostly covered in articular cartilage, and having very limited soft-tissue attachments and, therefore, little opportunity to develop an extraosseous blood supply for bone healing. The non-union status of cases of humeral intracondylar fissure creates sclerosis either side of the fissure compounding the poor biological environment and acting as a further barrier to neovascularisation.

In a retrospective, multi-centre study, it was reported that placing transcondylar lag screws was associated with a significantly lower infection rate compared to positional screws placed (Hattersley *et al.* 2011). The HIRS implant has variable pitches on

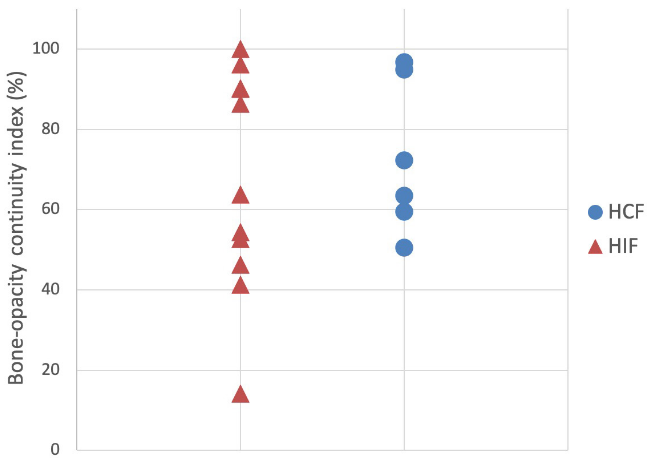

FIG 3. Dotplot of Bone-opacity continuity index (%) data for humeral intracondylar fissure (HIF) cases and humeral condylar fracture (HCF) cases

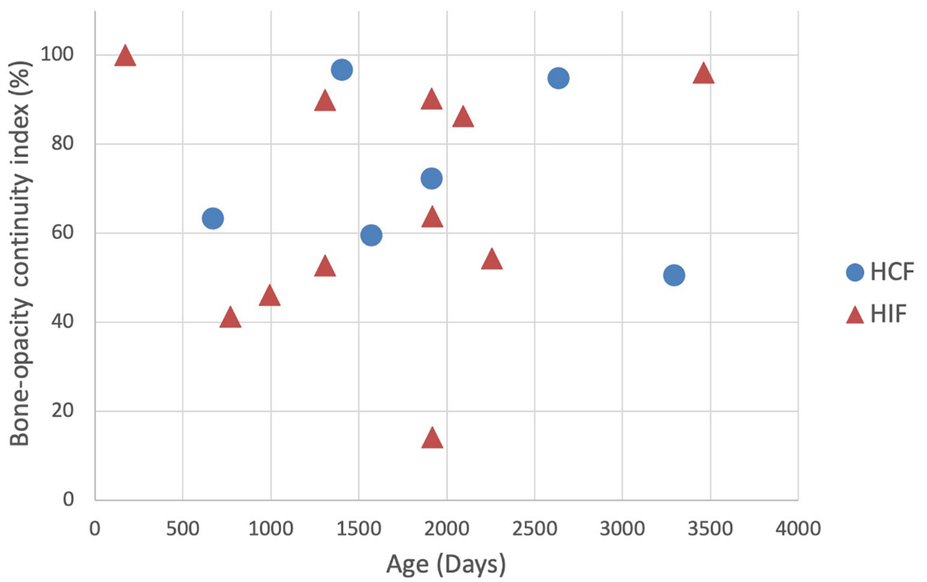

FIG 4. Scatterplot of bone-opacity continuity index (%) against age at the time of surgery for humeral intracondylar fissure (HIF) and humeral condylar fracture (HCF) cases

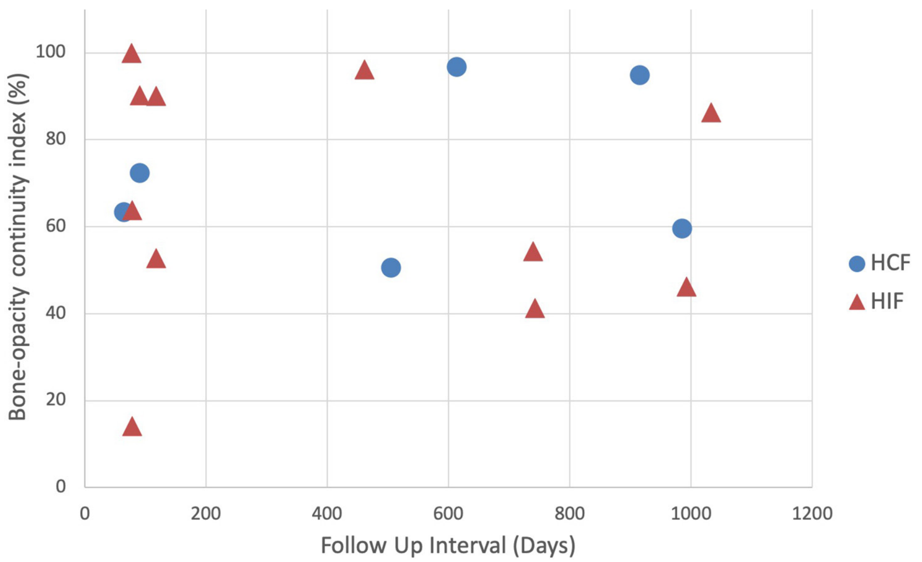

FIG 5. Scatterplot of bone-opacity continuity index (%) against follow-up interval (time from surgery to imaging) for humeral intracondylar fissure (HIF) and humeral condylar fracture (HCF) cases

the cis and trans threads, making it a self-compressing implant. In addition, the implant is made from titanium alloy; based on some experimental animal models (Arens *et al.* 1996), though not borne out by clinical studies, this may have some protective effect against surgical site infection compared to medical grade steel. In this study, surgical site infection occurred in 1 of 34 of humeral intracondylar fissure cases with follow-up. Previously reported infection rates for the surgical management of humeral intracondylar fissure have varied from not being listed as a complication (Butterworth & Innes 2001, Meyer-Lindenberg *et al.* 2002), to being relatively high in some studies, for example 30.4% in a multicentre retrospective study (Hattersley *et al.* 2011) and 3 of 14 (21%) in a recent case series (Moores *et al.* 2014). In the current series, all dogs at the primary centre received peri-operative antibiotic therapy, and 29 of 33 (88%) received post-operative antibiotics. This is compared to 28 of 43 (65%) in the report by Moores *et al.* (2014). In the current series, three of three fracture cases that did not receive a course of post-operative antibiotics, and none of the 11 that did, developed surgical site infection.

One of the more common minor complications in the management of humeral intracondylar fissure is seroma formation, with rates as high as 30% being reported (Hattersley *et al.* 2011). The HIRS implant is headless, potentially reducing interference with soft tissues, although this is not known to be the cause of seroma formation. In the current study, three of 34 of fissure cases developed seroma.

Although no statistically significant data are available in the published literature, there has been some suggestion that complications are less likely in cases of humeral intracondylar fissure when implants are placed in a medial to lateral direction, compared to a lateral to medial direction (Moores *et al.* 2014; Clarke *et al.* 2012). This is the advised standard operating procedure for application of the HIRS, and all but one implant was placed in this direction for the fissure cases in this study, and this may have contributed to the low infection rate reported here.

Implant-associated complications in the management of humeral intracondylar fissure include screw breakage (Butterworth & Innes 2001) and aseptic loosening (Moores *et al.* 2014). The HIRS implant design aims to minimise the risk of the latter by maximising bone-screw interface on both sides of the fissure: the trans thread has a coarse thread profile, similar to a "cancellous" type profile, and the cis thread has a large (5.8 mm) core diameter. One of 34 implants used in fissure cases, that is one in 48 overall, loosened in this study, and the cause was believed to be imperfect positioning. The pilot hole in this case was drilled via "freehand" aiming, without CT planning, an aiming device or fluoroscopic guidance: we advise against freehand aiming when using this system. The core diameter of the smooth section of the HIRS implant is 3 mm, slightly smaller than the 3.1 mm core diameter of an AO style 4.5 mm cortex screw. Screw breakage in humeral intracondylar fissure cases is likely to be a result of fatigue failure (Charles *et al.* 2009). Fatigue failure begins with crack initiation, a process that is more likely to occur when there is an uneven surface, *e.g.* surface defect or screw thread (Stephens *et al.* 2001). The smooth core of the HIRS implant may reduce the risk of crack initiation. However, the main strategy in avoiding fatigue failure in the HIRS is the optimisation of bone healing. By encouraging some healing of the fissure, the bone should become load-sharing with the implant, improving the longevity of both. In the shorter term, creating compression at the fissure should generate significant frictional forces that, again, should share some load with the implant. As the central shaft of the HIRS implant sits within a void, the stress on the implant may be distributed over some length of the shaft, rather than concentrated at the site of the fissure. Stress may concentrate where the core diameter of the implant changes: this transition is gradual to reduce this risk, and would be increasingly protected as the void refills with bone. Finally, titanium and its alloys have greater cycles to failure than surgical steel in low-strain environments. No screw breakages are reported in the current series, but a major limitation in this regard is the relatively short follow-up in some cases: in one case series, implant failures were seen between 11 months and 3 years after surgery (Charles *et al.* 2009), whereas follow-up times in this study ranged from less than 42 days to 3.5 years (1268 days). It would be necessary to follow all patients for at least 3 years to have a confident estimate of implant fracture rates. The short follow-up times in the multi-centre humeral intracondylar fissure group, most of which were less than 6 months, in particular, are a limitation of this study, and it is possible that the true complication rate for this group is being under-estimated.

There is justifiable concern regarding the healing capacity of humeral intracondylar fissure and related fractures, especially in adult dogs, and some surgeons prefer to place the largest, and therefore strongest and stiffest, implant possible, in a bid to minimise the risk of fatigue failure. However, in this study we report at least partial healing in all cases with CT follow-up, with the fissure accounting for <50% of the cross-sectional area of the condyle in 15 of 17 cases. Fitzpatrick *et al.* (2009) reported a minimum of 50% healing in seven of eight cases treated with bone graft and implants, based on CT. Moores *et al.* (2014) reported complete or partial healing in four of seven humeral intracondylar fissure cases and six of six condylar fracture cases treated with a shaft screw, based on CT. Therefore, healing is achievable, at least to some degree, in these cases and, as in all fractures, the goal should be to optimise the conditions for healing to occur. Unstable fixation might place an implant at risk of fatigue fracture, and might also lead to bone resorption and the formation of fibrous tissue at the screw-bone interface (Uhthoff 1973). Therefore, a stronger implant does not preclude implant failure, but makes it more likely to fail by loosening than by fracture. A limitation of this study is that sequential CT images were not collected. The single time-point CT assessment of bone-opacity continuity used here cannot be definitively assumed to be healed bone, as complete and accurate compression of the fissure or fracture, or interposition of mineral-opacity bone graft or substitute might result in a similar appearance. In order to be confident that the bone-opacity continuity demonstrated in these cases represents true healing, the follow-up imaging studies would have to be compared with immediate post-operative studies. Readers should be aware that this limitation is also shared with previous studies that report healing rates for humeral intracondylar fissure and humeral condylar fracture (Meyer-Lindenberg *et al.* 2002, Fitzpatrick *et al.* 2009, Moores *et al.* 2014).

A further concern in humeral intracondylar fissure and fracture cases, is that the underlying mechanism of the stress fracture is not understood. As these dogs rarely have other fractures, it appears more likely that humeral intracondylar fissures are fatigue fractures (normal bone subjected to abnormal forces) than insufficiency fractures (abnormal bone subjected to normal forces), though even this is conjecture because local biologic factors cannot be excluded. Assuming the fatigue fracture model is correct, the source of abnormal forces is not known. Possibilities include incongruency and kinematic factors, which are reported as risk factors for various stress fractures in people (Sherbondy & Sebastianelli 2006, Behrens *et al.* 2013). Surgeons rightly worry that whatever factors cause fissure formation in the first place are likely to persist after surgery and subject implants and healed bone to continued stress. However, the mechanical environment at the fissure is likely to be significantly altered by the implant. Therefore, the goal of surgery is, perhaps, to have an implant with good longevity, such that these stresses are shared between it and the healed bone for the lifetime of the dog.

Previous studies have used subjective, pseudo-quantitative methods to describe the extent of fissures and healing in humeral intracondylar fissure cases (Fitzpatrick *et al.* 2009, Moores & Moores 2017). We aimed to develop a truly quantitative method. It was beyond the scope of this study to fully validate this method, but, given the good inter-observer agreement of most measurements, we believe this method to be at least as valid as previously reported techniques.

In conclusion, The HIRS is associated with low complication rates when used for management of humeral intracondylar fissure and, based on CT imaging, there was at least partial osseous continuity across the condyle in all imaged cases at follow-up. Direct comparison to other systems and implants in the context of case-controlled studies would be useful to determine the true extent of the advantages of the HIRS over other implants, and long-term follow-up of cases will be required to assess the long-term success and complication rates. In the meantime, the current data are encouraging and suggests that HIRS is a good option for the management of humeral intracondylar fissures and humeral condylar fractures that might have been predisposed to by fissures.

Conflict of interest

Authors Walton and Innes are co-inventors of the Humeral Intracondylar Repair System and receive a royalty on implant sales. This has had no effect on the collection, reporting or interpretation of the data reported herein.

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