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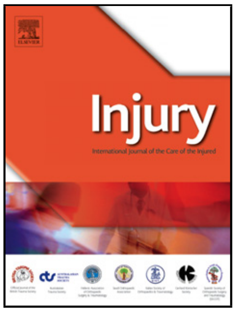

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Does Joint Architecture Influence the Nature of Intra-Articular Fractures?

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Abstract

Introduction: The architecture of joints has potentially the greatest influence on the nature of intra-articular fractures. We analysed a large number of intra-articular fractures with two aims: (1) to determine if the pattern of injuries observed supports our conjecture that the local skeletal architecture is an important factor; and (2) to investigate whether associated dislocations further affect the fracture pattern.

Methods: A retrospective study of intra-articular fractures over a 3.5-year period; 1,003 joints met inclusion criteria and were analysed. Three independent investigators determined if fractures affected the convex dome, the concave socket, or if both joint surfaces were involved. Further review determined if a joint dislocation occurred with the initial injury. Statistical analysis was performed using a one-way frequency table, and the χ^2 test was used to compare the frequencies of concave and convex surface fractures. The odds ratios (OR) were calculated to establish the association between the frequencies of concave and convex surface fractures, as well as between dislocation and either fracture surface involvement.

Results: Of the 1,003 fractures analysed, 956 (95.3%) involved only the concavity of the joint; in 21 fractures (2.1%) both joint surfaces were involved; and in 26 fractures (2.6%) only the convexity was involved ($\chi^2 = 1654.9$, df = 2, $p < 0.0001$). As expected, the concavity was 20.8 times more likely to fail than the convexity (11.2 - 36.6, 95% CI). However, the risk of fracturing the convex surface was 18.6 times higher (9.8 - 35.2, 95% CI) in association with a simultaneous joint dislocation, compared to those cases without a joint dislocation.

Conclusions: These results very strongly support the study hypotheses: the skeletal architecture of joints clearly plays a highly significant role in determining the nature of intra-articular fractures. Intra-articular fractures involving the convexity are much more likely to be associated with a concurrent joint dislocation.

Introduction

The laws of physics govern the forces responsible for traumatic injuries, and Newton's 3rd Law of Mechanics stipulates that for every action there is an equal and opposite reaction [6, 15]. Whenever loads are applied to one of our joints, those forces involved are distributed equally across the two opposing surfaces of that joint. If an intra-articular fracture should occur, one might reasonably expect an equal probability of that fracture involving either side of the joint. Yet common knowledge suggests this may not be true; consider the relative frequency of acetabular fractures compared to those involving the femoral head [7, 12, 13]. Are unspecified local factors responsible for this observed discrepancy in the pattern of articular surface involvement with intra-articular fractures?

The hip is generally considered the archetype of "ball and socket" joints [1, 16]. The external surface of the femoral head, normally almost spherical, is very closely matched in size, shape, and contour with the corresponding internal hemispherical surface of the acetabulum. Intimately apposed throughout the normal physiologic range of motion, these two surfaces are intended to fill two main functions [1, 16]. They glide smoothly over one another, to allow joint motion as an articulation; and they transmit force across the joint, as load-bearing members supporting the function of the other components of the skeleton.

With a typical "ball and socket" joint, it is convenient to consider the convexity of the "ball" to be analogous with a dome. Similarly, it is convenient to consider the "socket" to be analogous with a vault, often regarded as a three-dimensional arch. From the perspective of architecture, the design of a dome is best suited to resist loads external to its convex surface [21], much the same as the shape of an eggshell protects its contents [5, 9, 11, 14, 23, 24, 25]. With its inverted geometry, the design of a vault is also best suited to support loads applied external to its convex aspect, and when suitably loaded (as in supporting the roof of a building) it fills this role well [21]. Unfortunately, when that load is applied from within the concave aspect of the vault it would be expected to provide far less structural support, and to almost certainly fail under much smaller applied loads [5, 21].

Assume for the moment that the three-dimensional configuration of the joint surface, dictated by the architecture of the supporting bone, is in fact one of the most critical factors responsible for the failure mechanism of intra-articular fractures. If so, the vast majority of fractures would then affect the concave surface, while the convex dome would be relatively spared. Obviously high-energy traumatic injuries can be complex in nature, and other factors may also contribute. An associated joint dislocation can create conditions resulting in shear forces or point loading, conditions more conducive to injuries to the convex surface. Cognizant of the potential role of transient joint dislocation and impaction injuries to the convexity, further investigation of the relationship between dislocation and intra-articular fractures is warranted.

There are, therefore two hypotheses under investigation in this study: (1) in an analysis of a large number of intra-articular fractures, the distribution of the injuries sustained will disproportionately involve the concave surface; and (2) fractures involving the convex surface will occur more frequently in association with a concurrent dislocation.

Materials and Methods

We conducted a comprehensive retrospective analysis of intra-articular fractures at a major, metropolitan, tertiary referral hospital. Prior approval for this study had been obtained from our institutions Human Research Ethics Committee. We performed a systematic search of the IMPAX (Agfa HealthCare, Greenville, SC) radiology database, based on the radiologist's report text, imaging modality, patient demographics, and date. The IMPAX database was searched entering the relevant terms and Boolean operators: "intra articular fracture", "intraarticular fracture", and "intra-articular fracture". In addition, more specific parameters were used to expand the search in a more focused manner; we selected for particular joints or bones together with the word "fracture", such as "hip fracture", "acetabular fracture", or "femoral head fracture".

We have included all articulations where the radiographic profile demonstrates a convex surface paired with a concave surface clearly evident on at least one standard radiographic projection or CT slice. Joints we considered to broadly satisfy this description included the: hip, ankle, knee, shoulder, wrist (radio-scapho-lunate articulation), and elbow (radio-capitellar articulation); we also included the metacarpo-phalangeal and metatarso-phalangeal joints, as well as the proximal interphalangeal joints of both fingers and toes.

The following further inclusion criteria were applied: all intra-articular fractures between January 2010 and September 2013; patients over 18 years of age; principal mechanism of injury as given by the patient history most consistent with axial loading. Cases were excluded if (1) they involved other joints, not identified in the list above; and (2) the mechanism of injury was highly unlikely to be the result of an axial load. Three investigators (RS, SDS, and AL) conducted independent analyses of the relevant plain radiographs or CT scan images for each case; disagreement was resolved by consensus between the observers.

The initial search identified over 3,500 cases of an intra-articular fracture; over 2,500 were excluded because they were either duplicate cases or did not meet the specified inclusion criteria. The majority of these excluded cases were fractures involving spinal facet joints This resulted in a total of 1,003 cases that were selected for more complete review, and comprise the formal study set; demographic data was compiled for the study set, including age, gender, and anatomic location (Table 1). Study cases were further assessed radiographically, to identify the articular surface(s) involved: the convex surface (dome), the concave surface (vault), or both. The medical records of each case involving fracture of the convex surface (alone or together with the concave surface) were reviewed further, to look for common factors. Potential factors considered were mechanism of injury, joint dislocation, malignancy, medical comorbidities, steroid use, and smoking status.

Statistical analysis was performed with Systat (Version 13; Systat, Chicago, IL). Continuous variables are presented as means and standard deviations. Categorical variables are presented as percentages and frequencies. A one-way frequency table was created and the χ^2 test was used for two primary comparisons. First, we compared the relative proportions of concave surface fractures and convex surface fractures within our study set (Table 2). Second, we compared the percentage of dislocations associated with any fractures involving the convexity with the percentage of dislocations associated with fractures of the concavity in isolation (Table 3). Odds ratios (OR) were used to measure the association between: (1) the frequencies of concave and convex surface involvement; and (2) joint dislocation and the frequency of fracture of the convex surface.

To assess the possible relationship between mechanism of injury and fractures involving either the convexity (with or without concavity involvement) or involving the concavity alone, a randomly selected subset derived from the full set of isolated concavity fractures was used. Fisher's exact test (two-tailed) was used to analyse the resulting 2 x 2 contingency tables; only significant *p* values are reported (Table 4).

Results

The complete results are presented in Tables 2, 3, and 4. The three observers made a total of 3,009 independent assessments; there were only 24 instances where one observer differed from the other two (99.2% agreement).

In this study sample, 956 (95.3%) of the intra-articular fractures reviewed involved only the concave surface of the joint; in 21 (2.1%) cases both joint surfaces were involved; and in 26 (2.6%) cases only the convex surface was fractured. This predilection of the concavity to fail preferentially compared to the convexity was statistically highly significant ($\chi^2 = 1654.9$, df = 2, $p < 0.0001$). Combining all injuries, the concavity fractured in 977 cases, and the convexity fractured in 47 cases; the odds ratio was calculated comparing failure of the concavity to failure of the convexity, and the risk of sustaining a fracture of the concave surface was 20.8 times higher (11.2 - 36.6, 95% CI) than the risk of sustaining a fracture of the concavity.

Concurrent joint dislocation occurred in only 60 (6.3%) of the 956 cases where the concavity had failed in isolation; dislocation occurred in 26 (55.3%) of the 47 cases with fractures involving the convex surface. This predilection for the convexity to fail in association with a dislocation was statistically highly significant ($\chi^2 = 141.4$, df = 2, $p < 0.0001$). The odds ratio was calculated comparing failure of the convexity to failure of the concavity, and the risk of sustaining a fracture of the convex surface in association with a simultaneous joint dislocation was 18.6 times higher (9.8 - 35.2, 95% CI) compared to those cases without a simultaneous joint dislocation.

Discussion

After reviewing over 1,000 intra-articular fractures, the data presented here very strongly supports our primary study hypothesis: there is a statistically highly significant difference in the prevalence of failure of the concavity compared to the convexity. The three-dimensional configuration of the joint surface, as dictated by the architecture of the supporting bone, is clearly a critical factor in determining the distribution of intra-articular fractures. The concave surface fails over twenty times more frequently than the associated convex surface. As expected, the dome is able to tolerate the loads applied in the vast majority of injuries; the vault, however, is loaded from within and fails preferentially, unable to withstand the identical loads.

Many orthopaedic surgeons will of course recognize in principle the results demonstrated here, based on their own experience in clinical practice. Although perhaps intuitively obvious, this has never been systematically investigated or documented previously; to the best of our knowledge there are no prior relevant orthopedic publications.

Newton's Laws of Mechanics [6, 15] ultimately determine what injuries are potentially sustained during any traumatic event; only by considering the consequences of the laws of physics can we hope to have any genuine understanding of the injuries observed. Because every action has an equal and opposite reaction [6, 15], we know that the force transmitted across each joint is applied with the same magnitude on the two sides of every joint. Furthermore, that load is transmitted only across those surfaces that are in direct contact, and the contact area will necessarily be equal between the two closely matched joint surfaces. Therefore, the load per unit area will also necessarily be equivalent across the two involved surfaces. One might reasonably expect intra-articular fractures to be equally distributed between the two opposing joint surfaces. How, then, do we reconcile the huge discrepancy between these expectations and the findings observed in this study?

In our opinion, the three-dimensional configuration of the joint surface, as dictated by the architecture of the supporting bone, is the most critical factor in determining the distribution of intra-articular fractures. Consider the hip, a typical "ball and socket" joint [1, 16], as a structure with architectural homologues. The convexity of the "ball" (the femoral head) is analogous with a dome; the concavity of the "socket" (the acetabulum) is analogous with a vault, a three-dimensional arch. The design of a dome is best suited to resist loads applied external to its convex surface, just as the shape of an eggshell protects its contents [5, 9, 11, 14, 23, 24, 25]. Whatever loads are applied to the surface of the dome are converted to compressive forces [21] by the geometry of the macrostructure, and bone tolerates compressive loads very well. Despite its inverted geometry, the design of a vault is also best suited to resist loads applied external to its convex surface, and again these loads are converted to compressive forces [21]. However, when loads are applied from beneath the vault, through its concave aspect, the macrostructure is instead subjected to tensile forces. When loaded in tension bone provides far less structural support, and fails under much smaller applied loads [2, 3, 4, 8, 17, 22].

Although this rudimentary biomechanical analysis satisfies our expectations regarding a simple joint like the hip, the mechanism of failure in more complicated joints would be correspondingly more complex. It is unfortunately far beyond the scope of this study to attempt to address this any meaningful way, and sophisticated biomechanical studies will be necessary to evaluate this further.

Joints are, of course, not necessarily loaded in a neutral position, and we must also consider the implications of the direction of the applied forces within the physiologic range of motion. Again, the three-dimensional architecture of the surrounding bone remains the most significant factor in determining the result when supra-physiologic loads are sustained during trauma. Curiously, the femoral head is loaded as if it were a sphere throughout the entire normal range of motion; regardless of the orientation of the joint, the convexity of the dome persists. However, the socket-shaped acetabulum is highly sensitive to the orientation of any applied loads; although the concavity is always relatively weak compared to the convexity of the femoral head, in specific positions the supporting bone is at even greater risk. With the hip flexed, adducted, and internally rotated the posterior acetabular wall provides the least resistance, and fractures in this location are correspondingly most common [7, 12].

Fractures involving the convex surface are distinctly uncommon, but not rare; considering the overwhelming geometrical advantages of a dome-shaped sphere, why do we observe any at all? The convexity of an articular surface still fails under two alternative scenarios: (1) point loading, and (2) shear. Both of these abnormal loading configurations commonly occur during fracture-dislocations, and in this series joint dislocation was much more likely to be associated with injuries to the convex articular surface. In our series, the only significant additional factors associated with fractures of the convexity included concurrent joint dislocation, and punch injuries (Tables 3 and 4). These situations produced a potential direct impact to the articular surface or resulted in shear force across the joint, rather than true axial load. In our study set there were no instances of a fracture of the convexity in the absence of concurrent dislocation when the mechanism of injury was most consistent with a predominantly axial load.

Although impossible to prove under clinical conditions, presumably a posterior fracture-dislocation of a hip involves events in precisely that order: the posterior wall fractures, and a still intact femoral head then dislocates. As it does so, the spherical femoral head would initially be subjected to point loading by the fractured edge of the remaining intact portions of the posterior wall. When the femoral head slides past, it would then be at further risk of sustaining shear forces tangential to the articular surface. We believe this combination of pathological actions most likely results in those unusual injuries to the convex articular surface identified in this series.

This is most evident from our data regarding the association between fractures of the convexity and concurrent joint dislocation. When a concurrent joint dislocation occurred, a statistically highly significant difference was observed in the prevalence of fractures of the convex articular surface compared to fractures of the concave articular surface. Fractures of the convexity were greater than 18 times more likely to occur in association with a dislocation, when compared to those fractures without an associated dislocation.

The principal limitations of this study reflect the various assumptions made. Because these are clinical cases, the mechanism of injury would have been uncontrolled and difficult to define precisely. We were obligated to use the medical record to reconstruct events, based on the notoriously unreliable recollections of patients and observers. The true nature of the loading conditions responsible for these injuries would necessarily be highly complex and variable, even for specific joints. However, the results here are so overwhelmingly consistent and significant it is highly unlikely an in vitro cadaveric study would provide results any more compelling.

Admittedly, some of these joints are better defined as hinge joints, and some are much more complex than others. Unfortunately, the designation "ball and socket" joint is itself somewhat arbitrary; few articulations adhere to any rigid definition, and we have chosen to be more inclusive than restrictive. The hip best exemplifies the "ball and socket" configuration, but many other joints are composed of a convex surface paired with a closely matched concave surface. The shoulder adheres perhaps the least well, with a very large "ball" and a very shallow "socket"; nevertheless, we have included this joint as well, as it still clearly involves a convexity and a matched concavity. Perhaps indicative of the degree to which these two joints satisfy the designation "ball and socket", fractures involving the convex dome were most common in the shoulder and distinctly unusual in the hip (Table 2). In the sagittal plane the ankle appears much like a section of a "ball and socket"; however, in the coronal plane this articulation is more complex, and the dome of the talus has instead been described as a truncated cone, or frustum [10, 19, 20]. Regardless, and cognizant of the inherent limitations of generalizing across multiple anatomic locations, all of these joints are composed of a closely opposed pair of surfaces including a concavity and a convexity.

We recognize there is another plausible explanation for our observed findings, and there may in fact be a significant discrepancy in the density of the underlying bone on the opposite sides of these joints. The strength of cancellous bone is highly correlated with its apparent density [18], and it is possible that the density of the bone beneath the concave surface is substantially lower than the density of the bone beneath the convex surface. For example, if the talus is typically much denser than the adjacent distal tibial plafond it would almost certainly exhibit a similar distribution of injuries to that observed here, regardless of the bony architecture. Although an attractive alternative, further study will clearly be necessary to determine the relative contribution of bone density and joint architecture.

Finally, we note with great interest the apparent universal nature of this relationship (Figure 1). In our series, the resilience of the convex dome and the relative fragility of the concave vault were confirmed in every anatomic location investigated (Table 2), including the hip, knee, ankle, wrist, shoulder, elbow, and many smaller joints in both fingers and toes. We believe the findings reported here should be considered a fundamental property of intra-articular fractures; those fractures that deviate from this pattern warrant further consideration. Injuries to the convex articular surface imply shear forces or point loading developed during the injury event, and suggests a concurrent joint dislocation very likely has occurred.

Conclusions

These results strongly support both of the established study hypotheses. The three dimensional configuration of the articular surface, as dictated by the surrounding bony architecture, clearly plays a highly significant role in determining the nature of intra-articular fractures. The concave surface is far more likely to fail, and fractures involving the convexity are unusual injuries. Those fractures involving the convex articular surface are much more likely to have occurred in association with a concurrent joint dislocation. This predilection for the concavity to fail applies across a very broad range of different joints, including the hip, knee, ankle, wrist, and many smaller joints in both fingers and toes.

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Figure 1 Legend:

Representative CT scans of six different intra-articular fractures in six different joints, illustrating the significance of local geometry and joint architecture. The convex surface was far more resilient and unlikely to fail; the concavity was the site of failure in the over-whelming majority of cases. This was found to be true in every joint investigated, and is demonstrated here in the (A) hip, (B) knee, (C) ankle, (D) wrist, (E) talo-navicular joint, and (F) proximal interphalangeal joint of a ring finger.

Table I

Anatomic Location	Number of Cases	Age	Male	Female
Shoulder	**23**	**48 (19-89)**	**12**	**11**
Elbow (Radio-Capitellar)	**55**	**43 (18-88)**	**30**	**25**
Wrist	**414**	**51 (18-96)**	**194**	**220**
Hand	**143**	**36 (18-86)**	**106**	**37**
Hip	**108**	**48 (18-92)**	**80**	**28**
Knee	**78**	**45 (18-87)**	**49**	**29**
Ankle	**102**	**42 (18-87)**	**68**	**34**
Foot	**80**	**36 (19-86)**	**48**	**32**
Total	**1,003**	**45 (18-96)**	**587**	**416**

The demographic characteristics and the anatomic distribution of the complete study cohort of 1,003 intra-articular fractures.

Table 2

Anatomic Location	Number of Cases	Concave Surface Fractured	Convex Surface Fractured	Both Surfaces Fractured
Shoulder	**23**	**15 (65.2%)**	**7 (30.5%)**	**1 (4.3%)**
Elbow (Radio-Capitellar)	**55**	**55 (100%)**	**0 (0%)**	**0 (0%)**
Wrist	**414**	**408 (98.6%)**	**1 (0.2%)**	**5 (1.2%)**
Hand	**143**	**128 (89.5%)**	**11 (7.7%)**	**4 (2.8%)**
Hip	**108**	**107 (99.1%)**	**0 (0%)**	**1 (0.9%)**
Knee	**78**	**71 (91.0%)**	**5 (6.4%)**	**2 (2.6%)**
Ankle	**102**	**99 (97.1%)**	**1 (1.0%)**	**2 (1.9%)**
Foot	**80**	**73 (91.3%)**	**1 (1.2%)**	**6 (7.5%)**
Total	**1,003**	**956 (95.3%) ***	**26 (2.6%)**	**21 (2.1%)**

*$\chi^2 = 1654.9$, df = 2, $p < 0.0001$

In this large series of intra-articular fractures, the Odds Ratio of the risk of failure of the concave surface was 20.8 times greater (11.2 - 36.6, 95% CI) compared to failure of the convex surface.

Table 3

	Number of Cases	Concurrent Dislocation
Isolated Concave Surface Fractures	956	60 (6.3%)
Isolated Convex Surface Fractures	26	_
Simultaneous Convex/Concave Surface Fractures	21	_
Total Convex Surface Fractures	47	26 (55.3%) *

*$\chi^2 = 141.4$, df = 2, $p < 0.0001$

In this series of intra-articular fractures, the Odds Ratio of the risk of sustaining a fracture of the convex surface was 18.6 times greater (9.8 - 35.2, 95% CI) in association with a simultaneous joint dislocation, when compared to those cases without a simultaneous joint dislocation.

	Convexity Fracture	**Concavity Fracture in Isolation**
Total Vehicular Trauma	**16 (34.0%)**	**30 (31.6%)**
Automobile accident	4 (8.5%)	9 (9.5%)
Motorbike accident	8 (17%)	13 (13.7%)
Bicycle accident	4 (8.5%)	8 (8.4%)
Total Falls (*p* = 0.0186)	**12 (25.5%)**	**44 (46.3%)**
Fall – standing (*p* = 0.0042)	5 (10.6%)	31 (32.6%)
Fall – from height	7 (14.9%)	13 (13.4%)
Miscellaneous	**19 (40.5%)**	**21 (22.1%)**
Pedestrian struck	2 (4.3%)	4 (4.2%)
Sports Injury	2 (4.3%)	9 (9.5%)
Punch (*p* = 0.0399)	5 (10.6%)	2 (2.1%)
Crush	3 (6.4%)	2 (2.1%)
Other	7 (14.9%)	4 (4.2%)
Total	47	95

A randomly selected subset of the full set of concavity fractures was used to assess the possible relationship between mechanism of injury and fractures involving either the convexity or the concavity in isolation. There were significantly more falls from a standing height in the concave surface fracture group, suggesting a lower energy mechanism was responsible. There were significantly more punch injuries in the convex fracture group, suggesting direct impact may play a role. (Fisher's exact test with 2-tailed *p* values reported only if significant.)

Figure1A

Figure1C

Figure1D

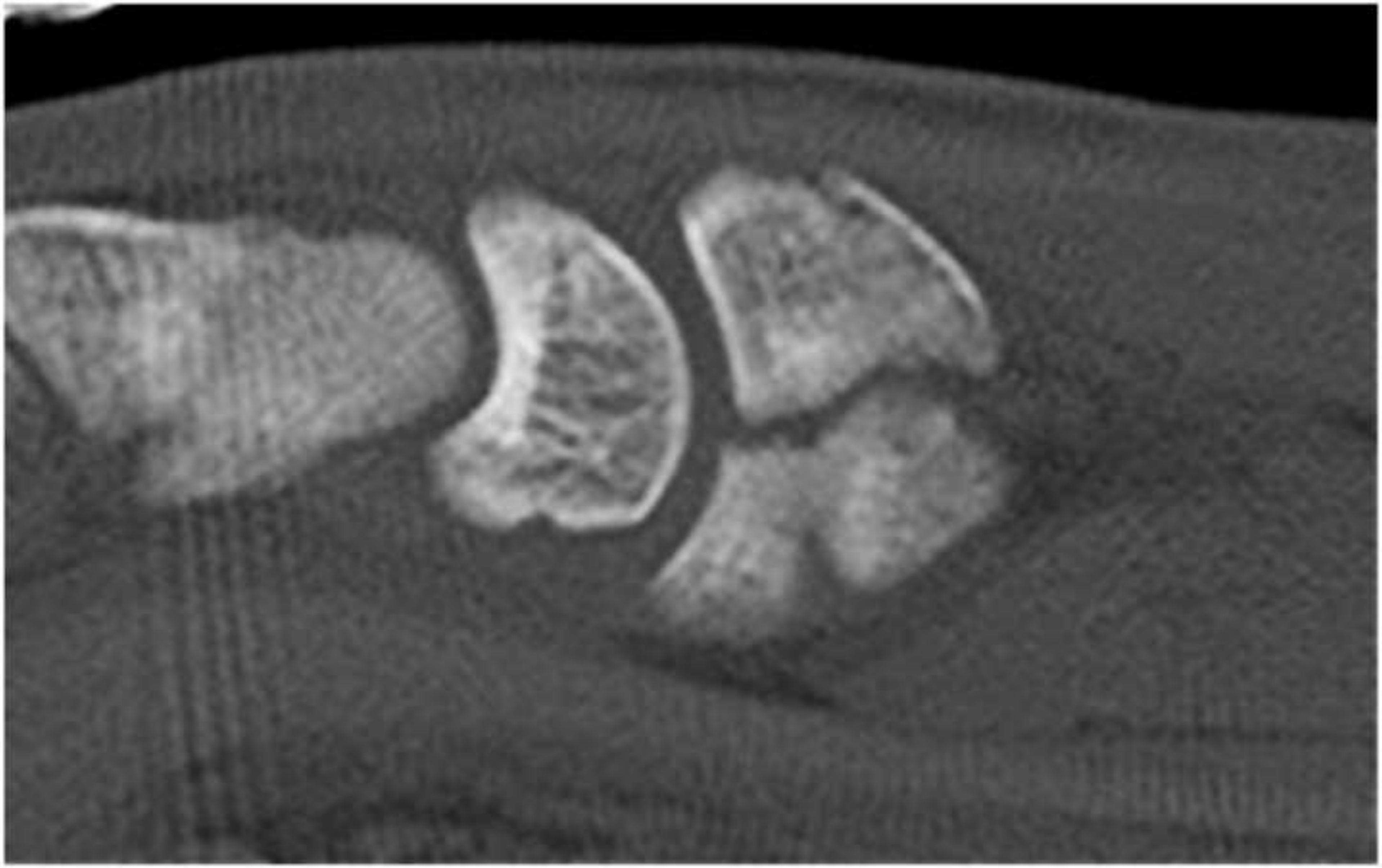

Figure1E