Common radiographic imaging modalities fail to accurately predict capitate morphology

Timothy Niacaris · Victor W. Wong · Ketan M. Patel · Michael Januszyk · Trevor Starnes · Michael S. Murphy · James P. Higgins

Abstract

Background There are three morphologies of the capitate based on its lunate and scaphoid articulations: flat, spherical, and V-shaped. Following a proximal row carpectomy (PRC), the capitate articulates with the lunate facet of the radius, altering contact biomechanics at the radiocarpal joint. Therefore, capitate morphology may influence contact pressures at the capitolunate articulation and influence clinical outcomes after PRC. However, it remains unclear which diagnostic imaging technique most reliably distinguishes between capitate morphologies.

Methods We evaluated the ability of plain radiographs, two-dimensional computed tomography (2D-CT), three-dimensional (3D)-CT reconstruction, and magnetic resonance imaging (MRI) to predict capitate type in 47 fresh frozen cadaver wrists. Two attending hand surgeons and one hand surgery fellow characterized capitate type based on each imaging modality. True capitate type was determined after gross dissection. We determined the reliability of each modality to predict capitate morphology.

Results We found all four imaging modalities to have a low sensitivity and specificity for predicting capitate morphology. Plain radiographs, 2D-CT, 3D-CT, and MRI had sensitivities/specificities of 0.46/0.57, 0.54/0.72, 0.54/0.52, and 0.56/0.65, respectively. All modalities had high negative predictive values for detecting the more rare V-shaped capitate subtype (range 91–94 %). Inter-rater reliability was poor for all modalities.

Conclusion These data suggest that plain radiographs, CT, 3D-CT, and MRI are not helpful in preoperative determination of true capitate morphology. Plain radiographs are as effective as more cost-intensive modalities in ruling out V-shaped capitates.

Keywords Anatomy · Capitate

Introduction

Alterations in carpal bone morphology have been shown to correlate with a predisposition for certain disorders of the wrist [5, 7, 8, 11, 15]. Numerous studies have examined the variable anatomy and articulations of the carpal bones in the hope of improving the understanding of wrist pathophysiology [9, 16, 17]. Yazaki et al. have described three variations of capitate morphology [18]. The flat-type capitate is the most frequent variant. It is characterized by an articulation between the capitate and lunate that is oriented transversely, with an approximately 90° offset between the articular surfaces of the capitolunate and scaphocapitate articulations. The second most common variant is the spherical-type capitate, which is characterized by a curved continuous articulation with indistinct borders between the capitolunate and scaphocapitate articulations. The V-shaped capitate is the most infrequent and is characterized by converging scaphocapitate and capitolunate articulations that form a sharp apex and an identifiable interfacet ridge.

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These variations in capitate morphology may have biomechanical implications on the radiocapitate articulation that forms following a proximal row carpectomy (PRC). Using pressure-sensitive film in a cadaveric PRC model, Yazaki et al. demonstrate that the contact surface area between the capitate and the radiolunate facet for V-shaped capitates (3 % of joint area) is approximately half that of the flat and spherical-type (6 and 5 % of joint area, respectively) capitates [18]. They propose that this decreased surface area results in increased contact pressures at the radiocapitate articulation and may predispose patients with V-shaped capitate morphology to early degeneration and clinical failure following PRC. These findings suggest that preoperative determination of capitate morphology may stratify patients predisposed to early PRC failure.

In this study, we sought to determine the most reliable radiographic modality that would accurately predict capitate type. We investigated the utility of plain radiographs, two-dimensional computed tomography (2D-CT), three-dimensional (3D)-CT reconstruction, and magnetic resonance imaging (MRI) [1, 2, 6]. The ability to predict capitate morphology preoperatively may prove useful to determine the influence of capitate type on clinical outcomes following PRC.

Materials and Methods

A total of 47 fresh frozen cadaver arms were used for this study. The mean age at death was 76 years (range 56–94 years). There were 25 male (53.2 %) and 22 female (46.8 %) specimens. There were 26 right and 21 left arms, including 14 matched pairs. All specimens were derived from arms cut through the mid-humerus. Each specimen was thawed and prepared for radiographic analysis. For each specimen, three views (anteroposterior, lateral, and oblique views) of the wrist were obtained using standard protocols for plain film imaging [7]. The wrists were held in neutral radioulnar deviation, and straight alignment was maintained between the long finger metacarpal, capitate, and radius. Images were captured using a digital X-ray system (58 kV, 2 mAs, Philips Healthcare, Andover, MA) and analyzed using OsiriX Imaging Software (Pixmeo, Geneva, Switzerland).

Computed axial tomography was performed using a Siemens 64-slice scanner (Siemens Healthcare Global, Cromwell, CT, USA) with bony algorithm and 1 mm slices (120 kV, 160 mAs, reconstruction interval 1 mm). Contiguous 2D images were analyzed in the coronal plane before being imported into a 3D reconstruction software program (Siemens syngo Multimodality Workstation). Magnetic resonance imaging was performed with the wrist positioned palm-side down using a Siemens Magnetom Symphony 1.5 Tesla

(Siemens) scanner. Wrist coil T1 and T2 sequences were used to obtain 3 mm slices in the coronal plane.

After imaging was completed, we performed a standard dorsal approach to the wrist to expose the radiocarpal and midcarpal joints. All dissections were performed with ×2.5 loupe magnification. Clinical photos were taken with the scapholunate ligament intact and with the scapholunate ligament transected to expose the entire contour of the proximal surface of the capitate. We completely dissected the capitate from the carpus and photographed the capitate in isolation using a digital camera (Canon PowerShot G11, Canon USA, Inc., Melville, NY). Following dissection of all capitates, each capitate was examined independently to determine the gross morphologic phenotype (flat, spherical, or V-shaped) (Fig. 1). Dissection findings were compared to each diagnostic imaging result.

Two attending level hand surgeons and one hand surgery fellow participated in radiographic classification of the capitates. All participants reviewed the classification system by Yazaki et al. before classification of the capitates in the study [18]. These results were tabulated for each modality and for all 47 specimens. After all capitates were assigned a classification type across all imaging modalities, the sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and accuracy were determined separately for each imaging modality (Fig. 2). Data for spherical and V-shaped variants were pooled to determine sensitivity and specificity for detection of general variation (from the most common flat-type capitate), as previously performed [7].

Inter-rater reliability among the three clinicians was evaluated using Fleiss' kappa [12]. Intra-rater reliability across the four imaging modalities was determined. Kappa scores of <0 = no agreement, 0–0.2 = slight agreement, 0.21–0.4 = fair agreement, 0.41–0.6 = moderate agreement, 0.61–0.8 = substantial agreement, and 0.81–1 = almost perfect agreement [4]. Strength of correlation was determined for capitate type between paired hands. Statistical analyses were performed using R statistical software (R Foundation for Statistical Computing. Vienna, Austria, www.R-project.org) and Microsoft Office Excel (Microsoft Corporation, Redmond, WA).

Results

Three of the 47 cadaver specimens could not be classified secondary to severe capitate degeneration, including one pair of matched hands. Of the remaining 44 wrists, there were 31 flat (66 %), 9 spherical (19 %), and 4 V-shaped (9 %) capitates as determined by gross dissection. We found a strong correlation between the true capitate morphology of paired hands (77 % agreement, $p=0.005$). Ten of 13 pairs had the same capitate morphology (nine pairs were flat and one pair had V-shaped capitates bilaterally).

Fig. 1 a Gross dissection of the three types of capitates shown in situ and b following complete dissection from the carpus. *Dashed lines* indicate angle of articulation between capitate and scaphoid/lunate. Different capitate types (flat, spherical, and V-shaped) are shown in each column. c Schematic of the three capitate morphologies as described by Yazaki et al. *Dashed lines* indicate angle of articulation between capitate and scaphoid/lunate. *L* lunate facet, *S* scaphoid facet
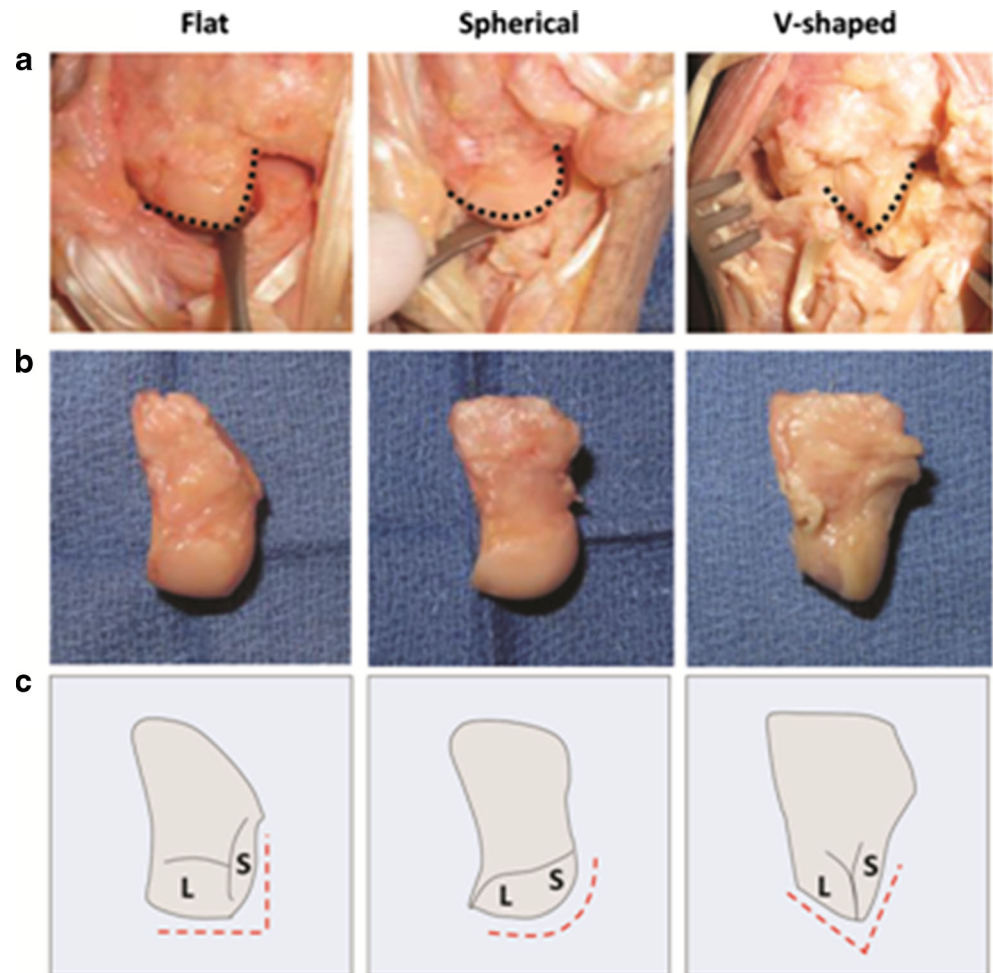
Plain radiographs, CT coronal images, 3D-CT reconstructions, and MRI coronal images were successfully obtained for each capitate type. Across all observers and capitate types, the sensitivity and specificity of plain radiographs were 0.46 and 0.57, respectively (Table 1). The use of 2D-CT images improved the sensitivity and specificity to 0.54 and 0.72, respectively. 3D-CT imaging had a sensitivity and specificity of 0.54 and 0.52, respectively. MRI had a sensitivity and specificity of 0.56 and 0.65, respectively. The PPV for determining capitate type for plain radiography, 2D-CT, 3D-CT, and MRI were 31, 45, 33, and 40 %, respectively. The NPV for determining capitate type for plain radiography, 2D-CT, 3D-CT, and MRI were 72, 79, 72, and 78 %, respectively. Overall accuracy for plain radiography, 2D-CT, 3D-CT, and MRI were 0.54, 0.67, 0.52, and 0.62, respectively.

For V-shaped capitates, the sensitivity of plain radiography, 2D-CT, 3D-CT, and MRI was 0.33, 0.17, 0.17, and 0.25, respectively. The specificity of plain radiography, 2D-CT, 3D-CT, and MRI was 0.94, 0.92, 0.93, and 0.91, respectively, to detect V-shaped capitates. The PPV for determining V-shaped capitate using plain radiography, 2D-CT, 3D-CT, and MRI were 57, 40, 38, and 18 %, respectively. The NPV for

determining V-shaped capitate type using plain radiography, 2D-CT, 3D-CT, and MRI were 94, 92, 93, and 91 %, respectively.

There were no clear trends in sensitivity or specificity across observers or with respect to level of training. Inter-rater reliability for determining capitate type was overall poor for plain radiography (−0.04), MRI (0.10), and 3D-CT (0.005). There was only slight agreement for 2D-CT (0.22). Moderate agreement (0.43) was found in assessing intra-rater reliability across these four modalities.

Discussion

Yazaki et al. have previously established a classification for capitate morphology consisting of three types [18]. They postulate that certain variations in capitate morphology might contribute to early clinical failures following PRC. In their study of 107 cadaveric wrists, 65 % were flat-type, 22 % were spherical-type, and 14 % were V-shaped capitates. A smaller study of 13 cadaver wrists found 38 % flat, 46 % spherical, and 15 % V-shaped capitates [7]. Our findings in 44 cadaver

Fig. 2 Representative diagnostic imaging modalities for each capitate morphology: **a** plain radiographs, **b** 2D-CT bone windows, and **c** MRI T1 weighted images. Different capitate types (flat, spherical, and V-shaped) are shown in each column. *Dashed lines* indicate angle of articulation between capitate and scaphoid/lunate
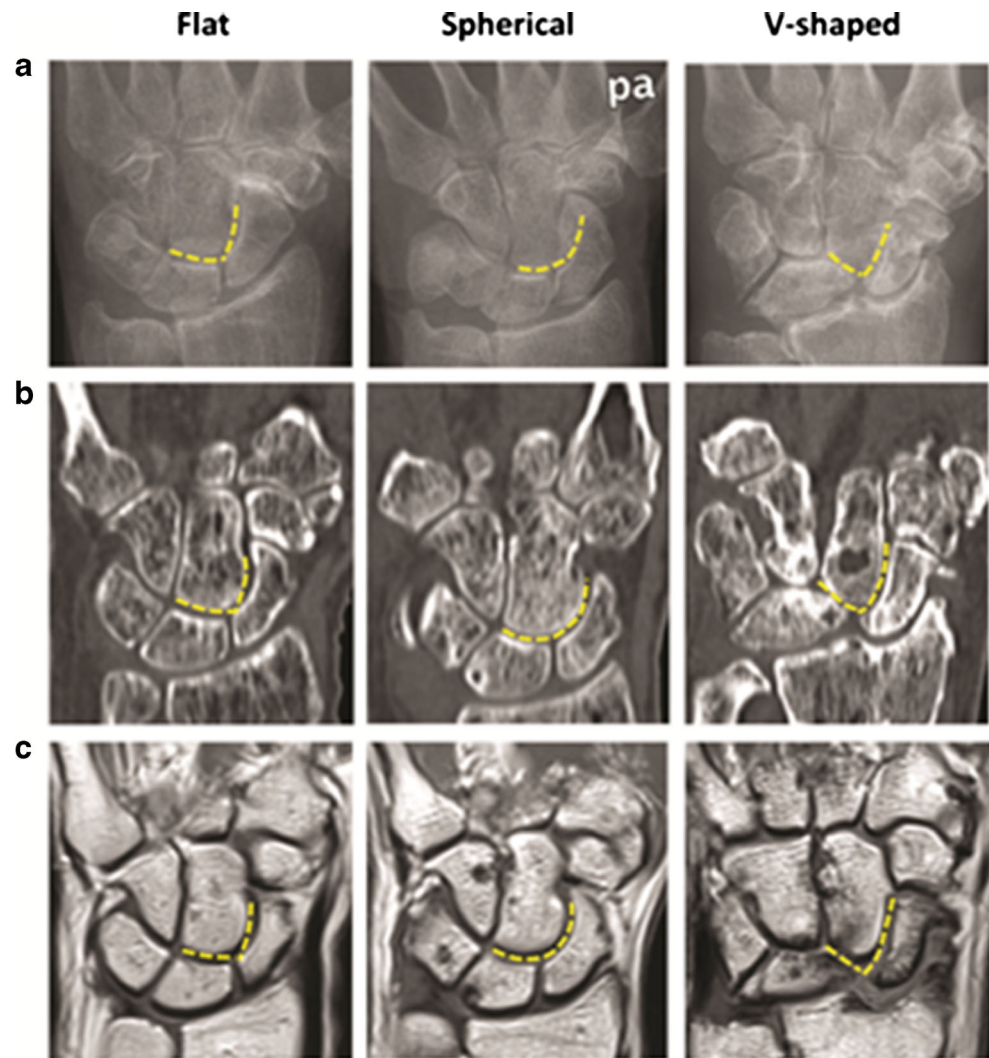
wrists paralleled these results in general (66 % flat, 19 % spherical, and 9 % V-shaped), demonstrating that V-shaped capitates are least common.

After PRC, the newly created articulation between the capitate and the radiolunate fossa is incongruent and the contact surface area depends on capitate morphology, particularly the proximal-most portion of the capitate surface [3, 10, 13]. In a

cadaver study, Yazaki et al. found that the V-shaped capitate had approximately half the surface area (3 % of available joint area) for articulation with the radiolunate fossa compared to flat (6 % of available joint area) or spherical (5 % of available joint area) shaped capitates [18]. They also reported increased contact pressures at the radiocapitate articulation with V-shaped capitates (6.5 MPa) compared to flat (4.0 MPa) or spherical (4.6 MPa) capitates. These findings suggest that V-shaped capitates may predispose the radiocapitate articulation to early cartilage degeneration and clinical failure following PRC.

For capitate morphology to be a clinically useful predictor of PRC outcome, it would be ideal to predict this morphology based on preoperative imaging studies. Also, clinical studies to identify the effect of capitate morphology on PRC outcome are dependent on knowing the relationship between preoperative imaging and the morphology of the capitate. We sought to identify the most reliable imaging modality to predict capitate morphology. Based on our results, plain radiographs, 2D-CT, 3D-CT, and MRI were all unable to reliably predict

Table 1 Accuracy for each imaging modality to detect variation in capitate morphology

Modality	Sensitivity	Specificity	PPV	NPV	Accuracy
X-ray	0.46	0.57	0.31	0.72	0.54
2D-CT	0.54	0.72	0.45	0.79	0.67
3D-CT	0.54	0.52	0.33	0.72	0.52
MRI	0.56	0.65	0.40	0.78	0.62

X-ray plain radiography, *2D-CT* two-dimensional computed tomography, *3D-CT* three-dimensional computed tomography, *MRI* magnetic resonance imaging, *PPV* positive predictive value, *NPV* negative predictive value

capitate morphology and specific detection of V-shaped capitates was poor. These findings corroborate a study by McLean et al. which concluded that direct visualization (i.e., surgical dissection) was necessary to determine V-shaped capitates [7].

Our data demonstrate that the most sensitive and specific modality for determining capitate morphology was 2D-CT. When restricted to V-shaped capitates alone, the sensitivity of CT in our study was only 0.17. However, 2D-CT resulted in 0.64 sensitivity and 0.82 specificity across all capitate types, compared to 0.90 sensitivity and 0.40 specificity in the McLean study [7]. These differences may be attributed to differences in imaging techniques or the lack of inter-observer agreement, as was reported in their study. The inability to predict capitate morphology, specifically the V-shaped capitate, calls into question the utility of common diagnostic imaging modalities in predicting capitate type preoperatively. Importantly, cost-intensive CT and MRI modalities were not substantially superior to plain radiography in distinguishing capitate types.

Although it seems logical that V-shaped capitates would potentially result in a less favorable radiocapitate articulation following PRC, one recent study suggests that capitate morphology may not be a critical factor in deciding whether to perform PRC. Tang et al. compared contact biomechanics in 13 cadaver wrists following PRC using pressure-sensitive film [14]. Comparing nine spherical capitates with four V-shaped capitates, there were no significant differences in contact area, pressure, or location in any wrist position. However, when examining V-shaped capitates alone, there were increased contact pressures with flexion and extension compared to neutral positions, findings not replicated in spherical capitates. This suggests that alterations in wrist kinematics based on capitate morphology may be better detected using dynamic studies.

During this study, we observed a degree of degeneration around the carpus that might be associated the presence of V-shaped capitates. It appears as if the apex of the V creates a wedge between the scaphoid and lunate. Whether the V-shaped capitate predisposes to scapholunate widening and possibly weakening of the scapholunate ligament, or whether widening of the scapholunate ligament associated with scapholunate injury leads to degenerative changes in the capitate resulting in a V-shaped morphology cannot be predicted by our study. There also appeared to be a strong correlation between capitate subtype in paired hands, suggesting that an intrinsic anatomic factor may underlie capitate morphology. Further studies will need to be conducted to determine if flat-type and V-shaped-type capitates represent a degenerative progression in wrist pathology.

Although the present study focused on bone morphology, the integrity of the cartilage is also important in determining carpal health. Another point to consider is whether the capitate subtypes are truly distinct entities or whether they represent a continuum of carpal degeneration. For example, V-shaped capitates may be the end result of persistent erosion and re-modeling at the midcarpal joint. Longitudinal studies examining capitate degeneration using non-invasive modalities such as 3-T MRI may provide important insight into the role of articular wear on capitate function. Future investigations are needed to clarify the clinical relevance of capitate morphology, specifically the V-shaped subtype, in degenerative wrist disease. Currently, however, there are insufficient data to propose a "permissible" V-shaped angle to predict post-PRC outcomes.

Limitations of this study include those inherent in using cadaveric specimens, the lack of precise definitions regarding capitate subtypes, and the analysis of radiographic imaging by non-radiologists. Future studies should establish objective radiologic measurements to define capitate morphology which may improve inter-observer reliability. The total number of V-shaped capitates in this study was small ($n=4$), thus limiting the ability to perform more robust statistical analyses. Furthermore, dynamic studies were not performed to investigate any functional differences between assigned capitate types.

In conclusion, this study demonstrates that plain radiography, 2D-CT, 3D-CT, and MRI are suboptimal modalities to assess capitate type. Although 2D-CT had the highest accuracy for detecting capitate variation, all modalities appear similarly effective at ruling out V-shaped capitates. These findings highlight the limitations of these diagnostic imaging modalities in determining capitate morphology to guide preoperative surgical decision-making.

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