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Radiographic measurements of the normal distal radius: reliability of computer-aided CT vs. observer radiograph interpretation.

ABSTRACT

We examined the reliability of a new computer-aided cone beam CT analysis and interobserver agreement of 2D radiographs for measuring radiographic parameters of the distal radius. Cone beam CT images of 50 uninjured radii were analysed using digital image processing. Reformatted 2D wrist radiographs were produced from the raw CT image data. The longitudinal axis, anterior tilt, radial inclination, and ulnar variance were measured by 15 physicians and compared to the computer-aided analysis. Intrarater reliability of the computer-aided analysis was evaluated on 33 unilateral wrists imaged twice. The reliability of computer-aided analysis was excellent (intraclass correlation coefficient [ICC] 0.94-0.96) while the interobserver agreement of 2D radiograph interpretation was good (ulnar variance, ICC 0.80-0.84) to poor (anterior tilt and radial inclination, ICC 0.20-0.42). Computer-aided cone beam CT analysis provides a reliable artificial intelligence tool for radiographic parameter determination, whereas physicians demonstrated significant variability especially in interpreting the angular parameters.

Level of evidence: III

INTRODUCTION

The treatment of distal radius fractures is guided by interpretation of radiographic measurements. The most commonly used anatomic radiographic parameters of the distal radius are anterior tilt, radial inclination, and ulnar variance. However, the reliability of visual estimation of these radiographic measurements is low (O'Malley et al., 2014). This is due to variable positioning of the upper extremity (Capo et al., 2009; Hardy et al., 1987; Palmer et al., 1982; Pennock et al., 2005), variable projections (Mekhail et al., 1996), and various reference points and inconsistent measuring techniques (Bernstein et al., 2018; Kreder et al., 1996; Medoff 2005; Palmer et al., 1982). As plain radiographs are only 2D approximations of the complex 3D geometry of the distal radius, the visual identification of bony landmarks is difficult and can cause conflicting interpretations. Furthermore, the expertise of the observer does not produce better reliability (Kreder et al., 1996, O'Malley et al., 2014).

3D imaging modalities provide better reliability of radiographic measurements, especially in evaluation of articular configuration and congruency (Christersson et al., 2016; Suojärvi et al., 2015). Due to the high spatial resolution and low radiation exposure, cone beam computed tomography (CT) is increasingly applied in musculoskeletal imaging. Several studies have demonstrated the value of using cone beam CT in evaluating wrist traumas and other pathologies (Gibney et al., 2019; Neubauer et al., 2016; Pallaver and Honigmann, 2019).

As an advanced 3D imaging modality, cone beam CT is an option for computer-aided image interpretation using mathematical modelling (Suojärvi et al., 2020). This study is part of a larger study project in which we aim to develop automatic cone beam CT image analysis to improve patient care with more accurate analysis of wrist fractures and other wrist pathologies. The aim of the study was to study the reliability of computer-aided cone beam CT image analysis and interobserver agreement of 2D radiographs among physicians in evaluation of the radiographic parameters of the normal distal radius.

METHODS

Image acquisition

This study consisted of two image groups. First, a group of 50 patients (29 men, 21 women, mean age 40 years, SD 16 years, range 17 to 82 years, left/right ratio 21/29) was retrospectively gathered from the radiographic database of the hospital emergency department to study the interobserver reliability of native radiographs for evaluation of radiographic parameters of the distal radius. This group was used to study the interobserver agreement among three different groups of observers and has also been analysed in a previous study reporting the detailed 3D radiographic anatomy of the distal radius (Suojärvi et al., 2020). The patients were imaged using cone beam CT to exclude fractures of the distal radius, ulna or the carpal bones after normal findings in primary radiographs. No additional imaging was performed for research purposes. The inclusion criteria included cone beam CT images presenting an intact radii with a minimum of 30 mm of distal radius visible in the image. The exclusion criteria included any signs of previous or current fractures or significant morphological changes of the distal forearm or the wrist. Informed consent was waived since the study was performed retrospectively with images from routine diagnostics. The wrists were imagined with the patient in a sitting position, the forearm in slight to moderate pronation, and the elbow extended according to the manufacturer’s instructions at that time. Standard 1.5-mm axial, coronal, and sagittal reformation images were included. The field of view was 13 × 16 cm, the isotropic voxel size was 0.4 × 0.4 × 0.4 mm and the isotropic resolution was 0.2 mm.

To study the intrarater reliability of the computer-aided cone beam CT image analysis, a second group of images was included. The unilateral wrists of 33 volunteers (19 men, 14 women, mean age 39 years, SD 9 years, range 25 to 60 years, left/right ratio 8/25) with no history of wrist or forearm trauma or chronic pain were imaged twice using cone beam CT (Planmed Verity, Planmed Oy, Helsinki, Finland). The imaging was performed with the wrist in neutral position, the shoulder at 90° abduction, the elbow in 90° flexion, and the hand palm down on the tray. Radiographic parameters of the distal radius were measured for these image pairs as described earlier using the cone beam CT image analysis software. The local ethics committee (Helsinki University Hospital's ethics committee, approval numbers HUS/1717/2019 and HUS/147/2019) and institutional review board approved the study and the volunteers provided written informed consent for their participation.

Analysis of cone beam CT images

The cone beam CT images were then analysed using a new image analysis software (Disior Ltd Helsinki, Finland). This is a recently developed artificial intelligence (AI) tool for computer-aided cone beam CT image analysis and parameter determination (Suojärvi et al. 2020). The software first registers a mathematical model of a wrist to the cone beam CT image, computes the location of measurement landmarks, and determines the longitudinal axis for each patient-specific radius model by generating an estimation of the axis (Suojärvi et al. 2020). The algorithm finds the proximal-to-distal centre curve of the radius shaft and uses robust line-fitting routines (Fischler and Bolles, 1981) for selecting a straight-line representative for the curve. The straight line with the least variation in direction represents the longitudinal axis. The optimal location for measuring the longitudinal axis is between 28.8 mm and 53.3 mm from the articular surface as previously reported (Suojärvi et al., 2020). Anterior tilt was measured from the most distal tips of the anterior rim of the lunate facet and the posterior rim of the scaphoid facet. Radial inclination was measured using the tip of the radial styloid and the central reference point (Medoff, 2005). Ulnar variance was measured using the central reference point and the most distal point of the distal ulna excluding the ulnar styloid process. The reference points used are presented in Figure 1 and the method of image analysis has been explained in more detail previously by Suojärvi et al (2020).

Reformatting of 2D radiographs

These 50 cone beam CT images were used to produce digitally reformatted 2D wrist radiographs with a postero-anterior (PA) and a lateral view from the raw cone beam CT image data as a summation image. In these reformatted images, windowing and weighting were first applied to the Hounsfield unit value scale of scans for optimizing image contrast for easy perception of bone shapes by the human eye. The Hounsfield unit is a relative quantitative measurement of radio density used in the interpretation of computed tomography images. The average intensity projection (AIP) was computed by exciting virtual rays from a plane grid through the scans. In an AIP image, each pixel holds the average value along the virtual ray. Shape emphasis was applied as the final step to the constructed images to sharpen bone boundaries within the limits of the resolution used in the scans. The resolution of the reformatted 2D wrist radiographs ranged between 1588 x 1367 (min) and 1811 x 1811 (max) pixels.

Projection directions for PA and lateral views were adjusted based on predetermined quality criteria for radiographs (Hardy et al., 1987). In the PA view, radius and ulna were aligned parallel and not overlapping each other. The joint spaces in the radiocarpal joint and the midcarpal joint were visible. In the lateral view, the radius and ulna were aligned parallel, overlapping each other, and the image was aligned along a line connecting the central reference point and the tip of the radial styloid process. Finally, images went through pseudo-random counter clockwise rotation of 5° to 20° in coronal plane to better simulate the real variation of hand positions in native radiographs in clinical practice (Figure 2).

Measurements on reformatted radiographs

Fifteen observers evaluated the reformatted native wrist radiographs (five hand surgeons, five general radiologists, and five general practitioners). Each observer interprets wrist radiographs and radiographic parameters of distal radius in their daily practice and all observers were familiar with national guidelines for management of distal radial fracture. The observers' average experience as a physician was 18 years (range 10 to 28 years) for hand surgeons, 21 years (range 12 to 29 years) for radiologists and 4 years (range 1 to 11 years) for general practitioners.

The observers independently marked and measured the following parameters for each of the 50 reformatted wrist radiographs: longitudinal axis of the distal radius in both the PA and the lateral view, anterior tilt (lateral view), radial inclination (PA view), and ulnar variance (PA view). To simulate their normal daily practice, the observers were not given any instructions on performing the measurements and landmark definitions. The measuring occurred in a hospital setting with normal lightning using a clinical workstation (Agfa, IMPAX 6, Agfa-Gevaert, Mortsel, Belgium). The image analysis tools for manually performed measurements of angles and distances were used as in clinical practice.

The differences between the measurements performed by the observers and the computer-aided digital measurements were calculated for the longitudinal axis in both PA and lateral views (degrees), anterior tilt (degrees), radial inclination (degrees), and ulnar variance (mm).

Statistical analysis

Different intraclass correlation coefficients (ICC) were used as metrics of reliability. In this statistical measure, an ICC value of 1 occurs with absolute agreement among observers and a value of 0 suggests the measurements were entirely random.

Intraclass correlation coefficients (ICC 2,1) were calculated to evaluate interobserver agreement among the three different groups of observers. To assess the reliability of the software in parameter determination, we calculated the ICCs for intrarater reliability. We determined that ICC values <0.50 indicate poor reliability, values from 0.50 to 0.75 indicate moderate reliability, values from 0.75 to 0.90 indicate good reliability, and a value >0.90 indicates excellent reliability.

Analysis of variance on the agreement among the three different observer groups was performed. Spearman's correlation coefficient was used to test the correlation between the difference in determining the longitudinal axis in either the PA or the lateral view and the length of the radius available for the measurement. Analysis of variance on this correlation was also performed. The radial length of 53.3 mm from the CRP was used as the threshold value, as this is the minimum length of the radius needed for reliable longitudinal axis determination (Suojärvi et al., 2020). Spearman's correlation coefficient was also used to test the correlation between differences in determining radial inclination and ulnar variance as the same ulnar reference point is often used for these measurements. A two-sample *t*-Test was performed to assess whether the error in measuring radial inclination or ulnar variance differs between the left and right wrists.

For the analyses of variance, Box-Cox transformation was applied to measurement errors to achieve approximately normal distributions. A Bonferroni multiple comparison test was used to assess the difference between the three groups.

A one-sample T-Test was used to test whether the errors in measuring the parameters were positive or negative compared to the digital measurements. This analysis was performed to assess if physicians are prone to evaluate the measurements as too great or too small.

To assess whether the observers' experience as a physician correlates to measurement errors, Spearman's correlation coefficient was used.

P-values <0.05 were considered statistically significant.

RESULTS

In the computer-aided cone beam CT analysis on the 50 radii in the first group the mean length of the radii measured from the central reference point proximally was 55 mm (range 32 to 91 mm, SD 16 mm). The average anterior tilt imaged in a slight pronation was 13° (range 6 to 22°, SD 3°), the average radial inclination 22° (range 16 to 26°, SD 2°), and the average ulnar variance -1 mm (range -6 to 3 mm, SD 2 mm). The differences between the measurements performed by the computer-aided cone beam CT analysis and the measurements performed by the observers using reformatted native radiographs are presented in Table 1.

Interobserver reliability of measurements on reformatted 2D radiographs.

Spearman's correlation coefficient showed a significant negative correlation (p=0.011) between determining the longitudinal axis in either the PA or the lateral view and the length of the radius available for the measurement. Shorter radii produced more difficulties in determining the axis. In the analysis of variance, the error was smaller if more than 53 mm of the distal radius was available for axis measurement (p=0.042). Spearman's correlation coefficient showed a positive correlation between deviations in determining radial inclination and ulnar variance (p=0.029). These parameters are assessed using the same reference point on the ulnar corner of the distal radius. A two-sample T-Test showed that there was no significant difference in determining ulnar variance in the left and right wrists (p=0.131) but the error in determining radial inclination was significantly greater when the measurement was made on the left wrist instead of the right (p=0.002). The one-sample T-Test showed that the errors in measuring the parameters were positive in evaluating the longitudinal axis in both PA and lateral views and radial inclination and ulnar variance. In evaluation of the anterior tilt, the error was negative and thus the angle was assessed as too small.

The results of the ICC (2,1) analysis for the groups of the three different observers are presented in Figure 3a. The ICC values for the three groups indicated good reliability for ulnar variance (> 0.8), moderate reliability for axis determination in the PA and the lateral view (>0.5), and poor reliability for radial inclination and anterior tilt (<0.5).

The variance analysis of measured parameters revealed differences between the groups of the observers. In determining the longitudinal axis in the PA view, there was a statistically significant difference between the radiologists and the general practitioners with the latter having slightly smaller error in the axis determination (p=0.045). The difference between the hand surgeons and the radiologists or the general practitioners was not statistically significant. The result was similar for radial inclination with the general practitioners performing better than the radiologists (p=0.012). For ulnar variance, the general practitioners had a smaller error than the hand surgeons (p=0.005). The hand surgeons had smaller errors compared to the radiologists and the general practitioners for the parameters assessed in the lateral view (longitudinal axis in the lateral view and anterior tilt) (p<0.001). The observers' experience as a physician did not correlate to measurement errors (p>0.05) except for the measurement of the longitudinal axis in the lateral view which showed positive correlation to experience (p=0.002). Longer experience produced more difficulties in determining the axis in the lateral view.

Intrarater reliability of computer-aided measurements

In the intrarater reliability analysis of the 33 wrist image pairs, the ICC values for the computer-aided cone beam CT analysis showed excellent reliability for the measurements of anterior tilt (0.94), radial inclination (0.96), and ulnar variance (0.94) (Fig 3b). In this image group, the mean anterior tilt in the intact radii of 33 wrists imaged in neutral position was 14° (range 10 to 20°, SD 2°) and the average radial inclination was 21° (range 17 to 26°, SD 2°). The average ulnar variance was -2 mm (range from -7 to 2 mm, SD 2 mm).

DISCUSSION

Our results indicate that computer-aided 3D cone beam CT analysis is very reliable for radiographic parameter determination of the distal radius, whereas physicians demonstrated considerable variability in interpreting radiographs. In particular, the reliability of the angular measurements was poor. These require initial determination of the longitudinal axis and are, therefore, more prone to errors. A longer visible and measurable length of the distal radius results in a more reliable estimation of the axis. The observer's specialization did not affect the reliability, which is consistent with earlier studies (Kreder et al., 1996; O'Malley et al., 2014).

In a study of measuring intact distal radii (Hollevoet et al., 2000), the intraobserver agreement was excellent with ICC values ranging from 0.90 to 0.94. However, the measurements were performed by only one observer. In a study analysing the effect of forearm rotation on the parameters (Pennock et al., 2005), good intra- and interobserver reliability (ICC values 0.89 and 0.91 for anterior tilt, 0.97 and 0.95 for radial inclination, and 0.88 and 0.85 for radial height, respectively) was shown. All three measurements were significantly affected by forearm rotation.

It appears that in these two studies the observers were given specific instructions on how to perform the measurements. This presumably improves the reliability and explains the higher ICC values compared to our study. Our study simulated the clinical reality of physicians conducting the measurements with individual variability. The ICC values of the computer-aided cone beam CT image analysis in our study were high compared to these previous studies.

AI, machine learning and deep learning have the potential to greatly improve musculoskeletal imaging in the near future (Langerhuizen et al., 2019). Machine learning algorithms have been applied to image interpretation and fracture recognition and deep convolutional neural networks have been shown to perform better than clinicians in detecting fractures on radiographs (Lindsey et al., 2018). Nowadays, convolutional neural networks can also localize fractures correctly in wrist radiographs (Thian et al., 2019). In clinical practice, it might not be difficult to detect a fracture. However, analysing the fracture characteristics and alignment properly may be challenging. In a study of adverse events in distal radius fracture treatment, most events were related to diagnostics errors and of these, the majority concerned incorrect assessment of the fracture displacement (Sandelin et al., 2018).

In our study, the anterior tilt measurements recorded by the computer-aided analysis (mean 14°) were equivalent to the mean values reported previously using conventional lateral view radiographs (Capo et al., 2009; Hollevoet et al., 2000; Medoff, 2005; Pennock et al., 2005). However, computer-aided analysis of the radial inclination measured from the central reference point was 21°. This is smaller compared to previous studies based on conventional radiographs (Hollevoet et al, 2000; Medoff, 2005; Pennock et al., 2005). This may be because the reference point at the ulnar border is often not specified. If the most proximal anterior rim is used as an ulnar reference point instead of the central reference point, the reported value of radial inclination is higher (Suojärvi et al., 2020).

In our study, the computer-aided analysis of ulnar variance (mean -1.5 mm) was performed using the central reference point and the wrist in neutral rotation. The average ulnar variance in the group of the 50 wrists that were imaged in a slight pronation was -1.4 mm and thus the difference was very small. The same reference point was used in the study by Medoff (2005) who reported an ulnar variance value of 0.6 mm. Other studies have used the method of a curved template (Palmer et al., 1982) or two perpendicular lines (Hollevoet et al., 2000) with mean values ranging from -0.9 mm to -0.13 mm. However, direct comparison of the reported values is not meaningful as the rotational position of the wrist is often not reported. For displaced fractures, the measurement of ulnar variance may be difficult to perform because the ulnar corner of the radius appears different with varying degrees of anterior or posterior angulation (Medoff, 2005).

Most previous studies on measurements performed on native radiographs have shown moderate or good reliability concerning extra-articular fractures, but the reliability for evaluating articular surface incongruence is poor (Kreder et al., 1996; Stirling et al., 2016; Suojärvi et al., 2015; Watson et al., 2016). A thorough review on the radiographic parameters of distal radius fractures showed marked variability in the actual description of performing the measurements (Lalone et al., 2015). In a recent review on the evidence regarding the accuracy of the parameters, only 5 of 5908 publications were found to be eligible (Jensen et al., 2019). The study concluded that there is no evidence available to support the accuracy of the radiographic measurements.

Our study has limitations. The first part of the study consisted of trauma patients and therefore may be subject to selection bias. However, the wrists included had no signs of fractures and showed no significant morphological changes in the radiocarpal joint. The study included only cone beam CT images of uninjured wrist bones. Further studies are needed to examine the reliability of the computer-aided CT analysis for measuring the parameters in fractured radii.

Due to the inherent problems in measuring the parameters particularly in 2D radiographs, contradictory guidelines on how to perform the measurements and little evidence of their accuracy, doubt must be raised on the ability of physicians to analyse the fractures correctly and to adhere to the current guidelines on acceptable radiological alignment of distal radius fractures. Cone beam CT is a relatively new imaging modality for evaluating wrist injuries and pathologies and in combination with computer-aided image interpretation it could provide a valuable tool for automated radiographic evaluation of the distal radius.

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Figure legends

Figure 1. Reference points used in the computer-aided measurements. The dotted line represents the segment where the longitudinal axis was determined.

P_0 = the tip of the radial styloid process

P_1 = the anterior ulnar corner

P_2 = the posterior ulnar corner

P_3 = the most distal point of the distal ulna excluding the styloid.

vt_1 = the most distal point on the anterior rim on the lunate facet

vt_2 = the most distal point on the posterior rim on the scaphoid facet

crp = the central reference point

Figure 2. Cone beam CT-based reformatted digital wrist radiograph and its rotation of 5°-20° in the coronal plane to better simulate the real variation of hand positions in native radiographs in clinical practice.

Figure 3.

a. Reliability (interobserver ICC 2,1 analysis) of the measurements in the three different groups of observers. Mean values and 95% CI.

b. Reliability (intraobserver ICC analysis) of the automated parameter measurements. Mean values and 95% CI.

ICC = intraclass correlation coefficient, AT = anterior tilt, RI = radial inclination, UV = ulnar variance, PA = longitudinal axis in posteroanterior view, LAT = longitudinal axis in lateral view