Validation of ultrasound measurement of the subacromial space using a novel shoulder phantom model

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Abstract

Ultrasound has a high degree of diagnostic accuracy in the assessment of the rotator cuff tendons. Increasingly, ultrasound is being used to measure other parameters of rotator cuff pathology, including the size of the subacromial space, or acromiohumeral distance (AHD). While this measure has been shown to be clinically reliable, no assessment of its validity has been carried out. This technical study reports on the development of a novel ultrasound phantom of the shoulder, and its use in validation of ultrasound measurement of AHD.

There was a close agreement between AHD measures using ultrasound and the true subacromial space of the phantom model, providing support for the construct validity of this measurement. The phantom model has good potential for further development as a training tool for shoulder ultrasound and guided injections.

Key words: ultrasound phantom, shoulder, acromiohumeral distance

Introduction

Self-reported prevalence of shoulder pain in adults averages between 15 and 20% in European population studies (Pribicevic 2012), with the most common diagnosis being disorders of the rotator cuff tendons. Ultrasound has been shown to be comparable in its diagnostic accuracy to magnetic resonance imaging (MRI) for identifying rotator cuff tears (De Jesus et al. 2009). Ultrasound findings in rotator cuff disorders include bursal thickening, tendon hypoechogenicity, and partial or full thickness tendon tears. Rotator cuff (RC) tendinopathy can lead to superior migration of the humeral, due to failure of RC stabilisation, and the resultant narrowing of the subacromial space may cause further tendon impingement (Lewis 2010). A reduction in the subacromial space has been reported in people with painful RC pathology (Saupe et al. 2006), and many interventions for RC pathology e.g. acromioplasty surgery, and exercise programmes, are founded on an attempt to increase the subacromial space, and thus relieve symptoms.

Radiographic examination has been traditionally used to assess for narrowing of the subacromial space in people with rotator cuff pathology, by measuring the acromiohumeral distance (AHD). However a recent systematic review found ultrasound to be the best method of AHD measurement, due to good evidence for its reliability, in contrast to the limited evidence for the reliability of radiographic methods (McCreesh et al. 2013). Reliability is an important property of a measurement, demonstrating consistency between measures and examiners; however, the validity of a measurement is also important to confirm the accuracy of the method. While studies have been completed comparing different radiological methods of AHD measurement in an attempt to provide some evidence for concurrent validity (Werner et al. 2008, Saupe et al. 2006, Azzoni et al. 2004), there remains no accepted ‘gold standard’ for this measurement, and no studies examining it’s construct validity. In a study aimed at assessing the amount of bone removal during arthroscopic subacromial decompression surgery, Tillander and Norlin (2002) intra-operatively measured AHD in people with and without subacromial pathology. While it was demonstrated that those with subacromial pathology had significantly smaller AHD, there was no comparison made to AHD measurement by any non-invasive method. While the intra-operative method provides a potential in-vivo method of assessing the construct validity of AHD measurement, there are numerous variables associated with the peri-operative condition e.g patient position, arm traction, and introduction of fluid, which prevent it from being an appropriate model for investigation. Validity of ultrasound imaging methods and measurements is commonly assessed by the use of an appropriate tissue-mimicking phantom (Thijssen et al. 2007, Koski et al. 2010). As no study to date has examined the construct validity of AHD measurement, the aim of this study was to evaluate the construct validity of ultrasound measurement of AHD, using a newly developed shoulder ultrasound phantom.

Materials and Methods

Development of the phantom:

A novel ultrasound phantom of the shoulder was developed. A DICOM Computerised tomography (CT) dataset of a shoulder was used to create a computerised 3D model of the superior half of the humerus and scapula. A 3D rapid prototyping printer (Vanguard HS HiQ SLS: 3D systems, Rockhill, USA) was used to print a bone phantom for each bone (humerus and scapula) out of DuraForm® PA (3D Systems, Valencia, CA, USA) (see Figure 1). The bones were placed in the correct alignment (with reference to the DICOM images) and rubber washers with epoxy resin were used to create the appropriate spacing. A custom mould was made of an appropriately sized shoulder, into which a compound containing gelatine, psyllium husk powder and chlorhexidine was poured. The bones were then embedded in this compound. Once the compound had set, the model was covered in latex paint to improve durability and resilience (See Figure 2). Our investigation of a sample of the two materials showed that the DuraForm® PA had a speed of sound of 1709 ms^{-1}, while the gelatine compound had a speed of sound of 1550 ms^{-1}, closely matched to the average speed of sound in soft tissue (1540 ms^{-1}). Acromiohumeral distance, measured as the shortest distance between the infero-lateral acromion and the adjacent part of the humeral head, was measured directly with Vernier callipers on the completed shoulder "joint" before it was embedded in gelatine. Five measures were taken.

Measurement validation:

Measurement of AHD on the shoulder phantom was independently undertaken by 2 musculoskeletal sonographers, blind to the true reference value of AHD in the phantom. Ultrasound examination was undertaken with a GE Logiq e ultrasound scanner (GE Medical, Wauwatosa, WI, USA) with a 7-12 MHz linear array transducer. An ultrasound image was taken with the transducer positioned along the line of the humerus, over the anterior part of the acromion, with the subacromial space and humeral head visible. The AHD was then measured as the shortest distance between the inferolateral edge of the anterior acromion and the humeral head, parallel to the acoustic shadow cast by the acromion (see Figure 3 for an image of AHD measurement from a normal shoulder, alongside an image from the shoulder phantom). Measurement of AHD was taken using on-screen callipers. Each examiner independently measured AHD on 5 separate images, with the probe removed and repositioned between scans.

Data Analysis

Descriptive values were calculated of the mean, standard deviation, and coefficient of variation (CoV) for the calliper measures, and the ultrasound measures (twice by Examiner 1, and a single set from Examiner 2). The values from Examiner 1 were used for the inter-method comparison. A box-plot was constructed to examine the spread of data points. Bland−Altman plot was constructed for the inter-method comparison between AHD measurement directly using callipers, and by ultrasound. As per the suggestion of Krouwer (2008), the difference between the methods were plotted against the calliper measurements (rather than against the mean of the two measures), as it was deemed the reference method. Wilcoxon signed Rank test was used to examine whether there were any differences between AHD measures by callipers and those acquired using ultrasound, as well as between testers.

Results

Table 1 presents the descriptive values of the AHD measurements by callipers directly on the bony 'joint' before embedding, as well as the ultrasound measures by both examiners. All methods also demonstrated excellent reliability, with CoV below 3%. There were no statistically significant differences between AHD measures with the callipers and ultrasound ($p=0.27$), or between intra-rater ($p=0.83$) or inter-rater ($p=0.09$) ultrasound measurements. The boxplot in Fig 4 illustrates good agreement across all measurements, all with medians within 0.5mm of each other and all measures falling within 1mm. The Bland-Altman plot in Fig 5 shows very good agreement with mean difference of only 0.14mm and limits of agreement lying between -0.44 to 0.72mm.

Discussion

This study investigated the construct validity of ultrasound measurement of AHD using a shoulder phantom. The Duraform® PA and gelatine-based phantom proved to be a very suitable model, with a similar look, shape and feel to a real shoulder joint, providing lifelike ultrasound images. Ultrasound-measured AHD values were very close to the true 'skeletal' measurement with callipers, confirming construct validity of the ultrasound measures. Reliability of the ultrasound AHD measures was also excellent.

Acromiohumeral distance in normal healthy shoulders ranges between 7 and 12mm (McCreesh et al. 2013). A reduction in AHD has been shown to be present in people with rotator cuff pathology, with reduction below 6mm thought to be indicative of a significant rotator cuff tear (Goutallier et al. 2011). Saupe et al. (2006) showed that AHD was associated with the degree of fatty degeneration of the rotator cuff muscles, which is an important predictor of surgical outcomes for rotator cuff repair. In a pilot study of people with shoulder pain undergoing physiotherapy, Desmeules et al. (2004) showed that there was a strong positive correlation between an increase in the AHD and functional improvement following rehabilitation. It is clear that further studies in symptomatic populations are required to ascertain the full clinical value of AHD measurement, but it may prove a useful diagnostic indicator in rotator cuff pathology.

Ultrasound has been shown to be a highly reliable method of AHD measurement both in healthy and shoulder pain populations, with CT and MRI demonstrating reasonable evidence for their reliability, but little evidence to support the reliability of radiographic methods (McCreesh et al. 2013). Each radiological method of AHD measurement has potential shortcomings. With radiographs, projection issues and bony overlap may lead to difficulty defining the area of measurement. During ultrasound examination, the acromion produces an acoustic shadow that may obscure the area of AHD measurement. The upright positioning for ultrasound and radiographs is consistent with the functional position for the shoulder, however for MRI and CT imaging the patient will assume the supine position, leading to a potentially smaller AHD measurement due to the lack of the effect of arm weight. A comparison of AHD measurement between MRI and radiographs was carried out by Saupe et al. (2006) who reported poor correlation between the methods, and consistently lower values for the MRI.

Despite the widespread use of diagnostic ultrasound imaging of the shoulder, there is no published work in the area of ultrasound phantoms of the shoulder. As a pilot phantom, this model had some limitations in terms of AHD measurement, namely the lack of soft tissue-mimicking components, and also the fact that the model was set in the 'supine' position, rather than the more usual upright position used for shoulder ultrasound. While we ensured good fixation of the bones, and undertook minimal movement of the phantom, we cannot guarantee that the subacromial space did not alter after embedding in the phantom. We did not undertake an assessment of the attenuation properties of the completed phantom, as we were not intent on creating a phantom with perfect tissue matching properties. Gelatin-water mixtures, with the use of husk material to create a speckle pattern, are well accepted as appropriate for the simulation of soft tissues. A full quantitative assessment of these mixtures has been published by Madsen et al (2005), which shows that the attenuation of our material should lie between 0.3 and 0.5 dB/cm/MHz, and thus be an acceptable soft tissue mimic. The ultrasound image of the phantom shares many characteristics of a true shoulder appearance, with the grainy appearance of the soft tissues and the reflective appearance of the bone model, with the appropriate degree of acoustic shadowing. With further development, the phantom has excellent potential as a model for training in diagnostic shoulder ultrasound, as it provided images that share similarities with clinical musculoskeletal images of the shoulder. It also has potential as a tool for practicing ultrasound guided shoulder injections. Further development would require addition of realistic tendon phantoms of the rotator cuff and biceps tendons, as well as the use of self-healing materials, in order to optimise the usefulness for injection training.

Conclusion

This study provides evidence for the construct validity of AHD measurement using ultrasound, using a novel ultrasound phantom. Further research is required to better understand the relative importance of AHD in shoulder pathology, and how it is affected by rehabilitation and surgery. The shoulder phantom has potential for further development as a training tool for ultrasound shoulder examination and ultrasound-guided shoulder injections.

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Figure Legends:

Figure 1: Computerised 3D shoulder model (left), and the printed out bones (right)

Figure 2: Completed shoulder phantom model

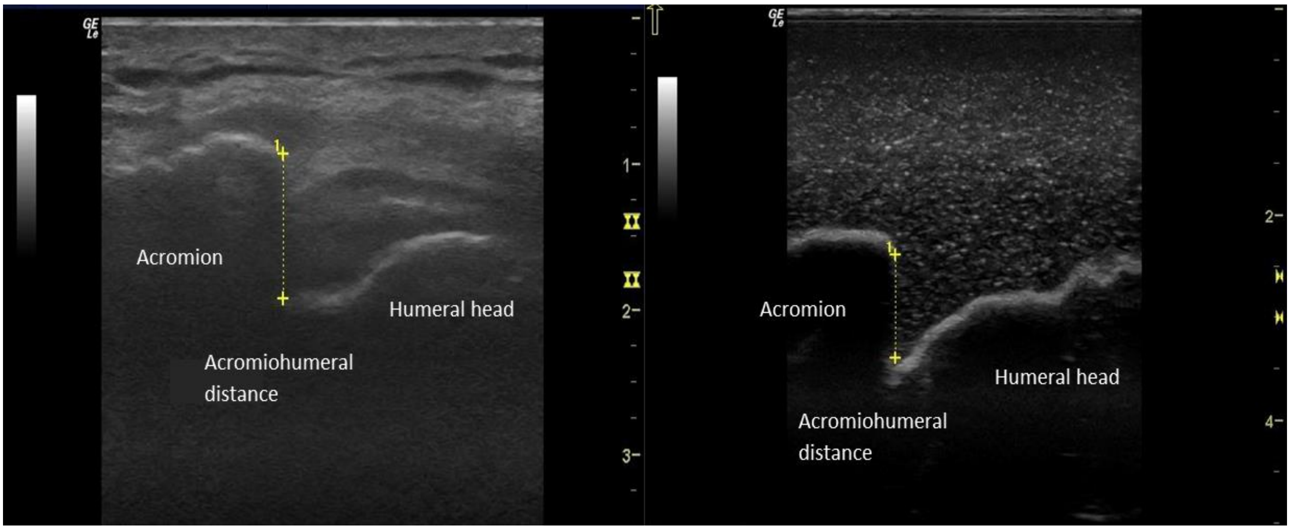

Figure 3: Ultrasound image of acromiohumeral distance (AHD) in a normal shoulder (A), and corresponding image of shoulder phantom (B)

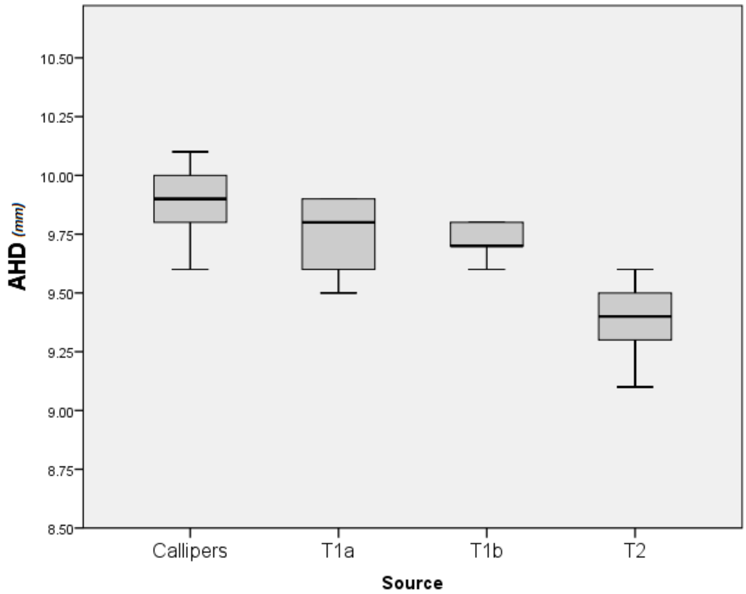

Figure 4: Boxplot illustrating acromiohumeral distance (AHD) measurements by callipers, and ultrasound (T1 = tester 1, T2= tester 2)

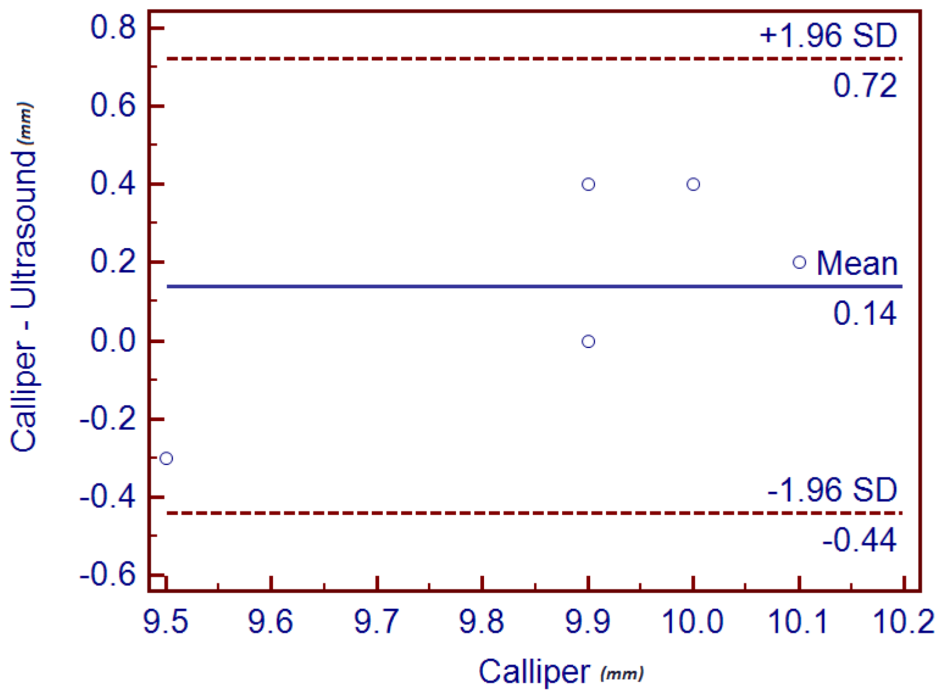

Figure 5: Bland−Altman plot comparing the acromiohumeral distance (AHD) measurement by callipers and by ultrasound (tester 1 measures). The mean difference was 0.14mm, and the limits of agreement were between -0.44mm and 0.72mm.

Table 1. Descriptive values for acromiohumeral distance (AHD) measurements of the shoulder phantom directly by callipers, and indirectly using ultrasound by two sonographers. Values taken from five repeated measurements in each case.

<table>
<tr><th rowspan="2"></th><th rowspan="2">Callipers</th><th colspan="3">Ultrasound</th></tr>
<tr><th>Tester 1 (time 1)</th><th>Tester 1 (time2)</th><th>Tester 2</th></tr>
<tr><td>Mean (mm)</td><td>9.9</td><td>9.7</td><td>9.7</td><td>9.4</td></tr>
<tr><td>SD (mm)</td><td>0.2</td><td>0.2</td><td>0.1</td><td>0.2</td></tr>
<tr><td>CoV (%)</td><td>3</td><td>1.9</td><td>0.9</td><td>2</td></tr>
<tr><td rowspan="3">Difference</td><td colspan="2">p = 0.27</td><td></td><td></td></tr>
<tr><td></td><td colspan="2">P=0.83</td><td></td></tr>
<tr><td></td><td colspan="3">P=0.09</td></tr>
</table>

Abbreviations: CoV= coefficient of variation; SD = standard deviation