Three-Dimensional Ultrasound Evaluation of Small Asymptomatic Abdominal Aortic Aneurysms

K. Bredahl a,*, B. Sandholt a, L. Lönn b,d, L. Rouet c, R. Ardon c, J.P. Eiberg a,d, H. Sillesen a,d

a Department of Vascular Surgery, Rigshospitalet, Copenhagen, Denmark
b Department of Interventional Radiology, Rigshospitalet, Copenhagen, Denmark
c Medisys, Philips Research, Suresnes, France
d University of Copenhagen, Copenhagen, Denmark

WHAT THIS PAPER ADDS

Current ultrasound (US) examination of abdominal aortic aneurysms (AAA) consists of antero-posterior measurement derived from a single still image. A major source of error associated with this method is that investigators will orientate the image plane differently. Furthermore, agreement between US and computed tomography (CT) is known to be inadequate. Three dimensional ultrasound (3D-US) offers the opportunity to perform real time simultaneous transverse and longitudinal imaging (dual plane imaging) and to establish a 3D-US AAA model from which both the maximum diameter perpendicular to the centreline and a partial volume can be calculated. This study demonstrates that 3D-US can estimate the AAA diameter perpendicular to the centreline as well as the AAA volume with an acceptable reproducibility and an improved agreement with CT.

Objective: Non-invasive and reproducible size measurements that correlate well with computed tomography (CT) are desirable in the management of small abdominal aortic aneurysms (AAA). Three dimensional ultrasound (3D-US) technology may reduce inaccuracy because of variations in orientation of the image planes and axis. This study aimed to determine any differences in paired size estimation associated with three 3D-US derived methods using 3D-CT as the gold standard. When CTA was not available, the patients were enrolled anyway to assess 3D-US reproducibility in terms of agreement between two physicians.

Methods: In the period from 1 March 2013 to 27 February 2014, consecutive patients with a small AAA, <5.5 cm for men and <5.2 cm for women, underwent 3D-US examination and three AAA size measures were obtained: dual plane diameter, diameter perpendicular to the residual sac’s centreline and a partial volume.

Result: In all, 122 consecutive US examinations were performed. Patients were excluded because of inadequate AAA size (n = 11) and for technical reasons (n = 11). Thus, 100 patients (F/M; 20/80) with a median maximum AAA diameter of 46 (range 31–55) mm were analysed. The mean US dual plane diameter and the 3D-US centreline diameter were 2.6 mm and 1.8 mm smaller than the mean 3D-CT centreline diameter, respectively (p = .003). The inter-observer reproducibility coefficient was 3.7 mm for the US dual plane diameter and 3.2 mm for the 3D-US centreline diameter (p = 0.222). For the partial volume, the reproducibility was 8–12%, corresponding to a diameter variability of ±3 mm. The median time used for post-processing of the 3D-US acquisition was 72 (range 46–108) seconds per examination.

Conclusion: 3D-US demonstrated an acceptable reproducibility and a good agreement with 3D-CT, and has the potential to improve future AAA management through more reliable ultrasound guided size estimates.

© 2015 European Society for Vascular Surgery. Published by Elsevier Ltd. All rights reserved.

Article history: Received 19 June 2014, Accepted 15 December 2014, Available online 4 February 2015

Keywords: Aortic aneurysm, Abdominal, Three dimensional, Ultrasonography, 3D ultrasound, 3D computed tomography, Volume measurement

INTRODUCTION

Ultrasound (US) is the preferred imaging modality for surveillance of small abdominal aortic aneurysms (AAA) and computed tomography (CT) is the preferred image modality for pre-operative assessment. There is sometimes poor agreement between the maximum diameter measured with 2D-ultrasound (2D-US) and the maximum diameter measured with CT.1

* Corresponding author. K. Bredahl, Department of Vascular Surgery, University Hospital of Copenhagen, Rigshospital-3111, Blegdamsvej 9, 2100 Copenhagen, Denmark.
E-mail address: kimbobank@yahoo.dk (K. Bredahl).
1078-5884/© 2015 European Society for Vascular Surgery. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ejvs.2014.12.022
It has been reported previously that a low inter-operator reproducibility coefficient of 3 mm is associated with the use of a two step standardised US protocol that includes electrocardiography (ECG) gated image acquisition and off line core reading.² It was found that, taking cardiac cycle and vessel wall delineation into account, the off line reading process only contributed to a minor part (1 mm) of the total variation. Instead, most of the variability was attributable to variations in image acquisition and orientation of the image plane between the operators. Three dimensional ultrasound (3D-US) has the potential to remedy this situation as the technique offers three new methods, each of which affords the operator the possibility to adjust for image plane mismatch. The first method is real time dual plane imaging, a modality that displays transverse and longitudinal images on the screen simultaneously. The second method is off line post-processing and construction of a 3D-model with a centreline of the AAA, by which the maximum diameter can be calculated perpendicular to the centreline. The third method is to use the same 3D-US AAA model to also estimate the maximum partial volume.

Using 3D-US instead of conventional ultrasound, improved agreement with 3D-CT in EVAR surveillance, was demonstrated recently.³ Encouraged by these findings, the present study was performed in a population with small AAA. The primary end point was the agreement between the maximum diameters of the two US methods using a 3D-CT centreline determined maximum diameter as the gold standard. The secondary end points were:

1. Determine the reproducibility of dual plane US diameter assessment and 3D-US determined maximum diameter perpendicular to the centreline.
2. Estimate the agreement between the maximum partial volume assessed with 3D-US and 3D-CT and determine the reproducibility of 3D-US partial volume assessment.
3. Assess the impact of increasing aneurysm size, dilatation during the cardiac cycle, and body mass index (BMI) on the inter-operator and inter-modality range of variability (ROV).

MATERIAL AND METHODS

Study design

A prospective, single centre study was designed comparing three 3D-US measures using 3D-CT as the gold standard. When available, CTA was used, when not, the patients were enrolled anyway to assess 3D-US reproducibility in terms of agreement between two physicians. The US dual plane diameter was available on cart, whereas the two other US measures were established after off line post-processing of the 3D-US acquisition, described in detail later (Fig. 1). The study was approved by the local ethical committee of Copenhagen (H-4—2013—037).

All US examinations were performed by two physicians who use 3D-US on a daily basis. The first physician (KB) was familiar with 3D-US of EVAR from previously published studies.³,⁴ The second physician (BS) was an experienced sonographer with 3D-US experience from imaging of the carotid arteries who performed ten supervised 3D-US AAA examinations before recruitment. The physicians read the referral information, but were not allowed to evaluate any concomitant CTs, before the US examinations were completed. Patients were examined in a mutually blinded setup including resetting of the US system between the examinations.

Patients

In the period from 1 March 2013 to 27 February 2014, consecutive patients with small native asymptomatic AAA (>3.0 cm) were prospectively and consecutively enrolled into the study if their aneurysm diameter was less than 5.5 cm for men and less than 5.2 cm for women. These sizes are the generally accepted thresholds for conservative treatment.⁵ Patients with incidental AAA findings on CT...
were included for 3D-US versus 3D-CT comparison. Patients who were newly referred or scheduled for routine surveillance of a known small AAA without CT were only included when the second physician (BS) was available for reproducibility assessment. Moreover, patients were excluded if bowel gas or obesity made insonation inadequate; in particular if visualisation of the circumferential aortic wall on several images made at least one of the physicians lose confidence in the 3D AAA reconstruction. Patients with aortic-iliac aneurysms were excluded if the abdominal and iliac component were not clearly distinguishable on ultrasound.

**Ultrasound imaging**

Patients did not routinely undergo any specific preparations such as fasting before the US examination. After 10 minutes of rest, patients were placed in a supine position. All US examinations were performed using a commercially available 3D matrix transducer (X6–1 xMATRIX, Philips Healthcare, Bothell, WA, USA) and US system (Philips iU22 Ultrasound System, Philips Healthcare, Bothell, WA, USA).

First, a US dual plane diameter was measured on the transverse display from the leading edge of the adventitia anterior wall to the leading edge of the adventitia posterior wall in peak systole. To obtain a correct antero-posterior image plane on the transverse display, it was checked that the AAA was horizontal on the longitudinal display (Fig. 1). Anatomic references to the lumbar vertebrae were not used.6

Next, the 3D-US acquisition was performed during breath hold (<2 seconds) while the transducer was kept in a firm stable position above the cross section showing the maximum diameter. The 3D-US acquisitions were then transferred to a workstation and later handled in the experimental semi-automatic 3D software (Fig. 1).

**Computed tomography**

Some patients were referred because CT had revealed a coincidental AAA. In these cases, the CTS were used as the gold standard when US and CT were compared and the entire aneurysm was displayed, provided the slice thickness was less than 5 mm and the CT was performed within 3 months of the US examination.

**3D reconstruction, centreline and volume estimation**

The 3D-US acquisitions as well as the native CT slices were handled using experimental semi-automatic 3D software (AAA prototype, version 2.0, Medisys, Philips Research, Suresnes, France). The physicians handled each of their own 3D-US acquisitions. First, they had to manually encircle the AAA at the most proximal and distal recognisable part of the aorta as well as one in the middle, thus facilitating an automatic 3D reconstruction using the inner vessel wall delineation. The software allowed for manual adjustments before a centreline of the 3D-model was generated and the maximum diameter perpendicular to this centreline was defined as the 3D-US centreline diameter.6 Thus, on the orthogonal cross section, the diameter was not restricted to a specific axis, the antero-posterior axis, but could be established in any direction.

No specific anatomic landmarks were used for the beginning or ending of the partial volume measurements. Instead, the maximum partial volume was defined as the maximum achievable volume that could be obtained between two orthogonal cross sections with a mutual distance of 60 mm on the centreline.

Defining a maximum partial volume with a length of 60 mm was a trade off between including as much of the aneurysm as possible and maintaining as many patients for this analysis as possible. The principle used for partial volume calculation has been described in detail in a previous publication.4

The physicians (KB and BS) had separate workstations, and each handled their own 3D-US acquisitions in a mutually blinded setup. The paired 3D-Us and concomitant CTS were post-processed off line with a minimum time delay of 14 days to preclude potential bias caused by the same physician (KB) handling both examinations. Similarly, a time delay of 14 days was interpolated between the first and the second 3D-US acquisition for the intra-observer assessment.

**Statistics**

Inter-modality, inter- and intra-observer variability were presented using Bland Altman plots where the differences between measurements made on the same subject were plotted against the mean outcome, showing the mean difference and the upper and lower limits of agreement (LoA) given by the mean ± 1.96 × standard deviation (SD). The range of variability (ROV) was defined as 1.96 × SD.

Student’s paired t test was used to compare means and mean differences. To test whether the observed inter-modality ROV and inter- versus intra-observer variability were different, Pearson’s correlation coefficient was calculated for the sum and difference of the paired differences made on the same subject.

To assess the impact of increasing aneurysm size, pulse propagation and body mass index (BMI) on the ROV, linear regression was used, plotting the absolute values of the variability against the maximum diameter obtained with 3D-CT, the pulse propagation and the BMI, respectively. To assess the impact of image quality (good vs. acceptable), the Student’s t test was used.

Statistical packages SAS v. 9.3 (SAS Institute Inc., Cary, NC, USA) and Graph Pad Prism v. 6 (GraphPad Software, Inc., San Diego, California, USA) were used for graphical presentation.

**RESULTS**

**Patients**

Patient selection is shown in Fig. 2. During the 12 month enrolment period from March 2013 to February 2014, 122 consecutive US examinations were performed (Fig. 2). Eleven patients were excluded because of the size of their AAA (Fig. 2). The real time US dual plane maximum
Diameter inter-modality variability

Fifty-four patients were included in this analysis (Fig. 2). The mean 3D-CT centreline diameter — the gold standard — was larger than both the mean US dual plane diameter (2.6 mm, \( p < .001 \)) (Fig. 3A) and the mean 3D-US centreline diameter (1.8 mm, \( p < .001 \)) (Fig. 3B). This 0.8 mm improvement of the difference gained by using the 3D-US centreline diameter rather than the US dual plane diameter was statistically significant (95% CI 0.4—a 1.2 \( p = .003 \)). However, the ROV of 3.1 mm achieved when measuring the 3D-US centreline diameter was not different from the 3.4 mm ROV of the US dual plane diameter \( (p = .392) \).

Increasing AAA size was shown to significantly impair the agreement between the US dual plane diameter and the 3D-CT centreline diameter (slope = 0.119, \( p < .001 \)) by 1.2 mm per 10 mm. However, this correlation was less pronounced when the 3D-US diameter was measured, where the difference increased by 0.9 mm per 10 mm increase in maximum diameter (slope = 0.087, \( p < .0005 \)). Neither pulsatility nor BMI impaired the agreement.

Diameter inter-operator variability

Seventy-nine patients were included in the inter-operator and intra-operator analysis (Fig. 2). The mean difference between the two physicians’ measurements of the US dual plane diameter of the same AAA was 0.04 mm \( (p = .834) \) and the ROV was 3.7 mm (Fig. 3C). The mean difference for 3D-US centreline diameter between the two physicians, who each handled their own 3D-US acquisitions, was —0.4 mm \( (p = .017) \) and the ROV was 3.2 mm (Fig. 3D). These inter-operator mean differences (0.04 mm versus —0.4 mm, \( p = .061 \)) and the ROV (3.7 mm vs. 3.2 mm, \( p = .222 \)) were not different from each other.

The inter-operator variability was not affected by image quality, increasing aneurysm size, BMI, or pulsatility.

Diameter intra-operator variability

Intra-operator assessment was performed for one physician’s 3D-US centreline diameter measures (KB). The mean intra-operator difference was —0.2 mm \( (p = .221) \) with SD = 1.5 mm and a corresponding upper LoA of 2.7 mm and a lower LoA of —3.1 mm.

The mean intra-operator difference was not different from the mean difference observed in the inter-operator assessment \( (p = .214) \), nor were the ranges of variability \( (p = .317) \).

Volume assessment

Apart from eight patients already excluded because of poor image quality and three patients excluded because of aortic-bi-iliac aneurysms (Fig. 2), a partial volume with a length of 60 mm could not be processed in six patients, who were therefore excluded from this analysis, which resulted in a technical success rate for volume assessment of 85% \( (94/111) \).

The difference between 3D-CT and 3D-US was 8.2 mL \( (p < .001) \) and LoA ± 12% \( (Fig. 4) \). The absolute difference between 3D-CT and 3D-US increased \( (slope = 0.039, p < .001) \) corresponding to 3.9 mL per 10 mm increase in...
Figure 3. The difference of paired measurements plotted against their mean. SD: Standard deviation; LoA: Limits of Agreement.

Figure 4. Volume assessment: The curved dotted lines represent the change in volume of a 6 cm cylinder if the cylinder’s diameter varied ±3 mm. This corresponds to the limits of agreement associated with ultrasound diameter measurement. For more information, please see statistics. LoA: Limits of Agreement.
maximum diameter, but was unaffected by increasing BMI (slope = 0.092, \( p = .577 \)).

The mean inter-observer difference was \(-0.5 \text{ mL} \) (\( p = .344 \)) with the LoA within 11%. The mean intra-observer difference was \(0.1 \text{ mL} \) (\( p = .716 \)) with the LoA within 8%. The intra-observer ROV of 6.6 mL was significantly lower (\( p = .010 \)) than the inter-observer ROV of 8.7 mL (Fig. 4).

If the entire aneurysm had been used rather than partial volume assessment, it would only have been possible to analyse 39 (39%) patients because of limited image quality at the extreme limits of the electronic 3D-US sweep.

**Clinical implications of different image modalities**

In this study, the clinical decision was based on the US dual plane maximum diameter, and all patients had an aneurysm size that allowed continued ultrasound surveillance rather than prophylactic surgery. Re-evaluations of the subpopulation were conducted by measurement by all three imaging modalities (\( n = 54 \)) for determining a clinical treatment decision, and 13 patients were identified (F/M; 3/10) who had an US dual plane diameter within 5 mm of the threshold for surgery (5.0–5.5 cm for men and 4.7–5.2 cm for women). Using the gold standard of this study, 3D-CT instead of US dual plane imaging, 9 out of 13 patients (69%) would be considered for surgery. If the clinical decision had been guided by the measurements obtained by the 3D-US diameter rather than the US dual plane diameter, 3 out of these 13 patients (23%) would have been considered for surgery.

**DISCUSSION**

Correct determination of the diameter of an AAA is crucial in the management of AAA; and for small AAAs in particular, the need for a non-invasive outpatient imaging modality that is in close agreement with CT is of topical interest. This study demonstrated, first, that 3D-US can reduce the well known disagreement about the maximum AAA diameter between US and CT to only a few millimetres; second, that the 3D-derived methods were associated with an acceptable inter-observer reproducibility coefficients of 3.2–3.7 mm; and, third, that with a post-processing time as low as 1–2 minutes, “the 3D mindset” lends itself easily to clinical implementation, especially if all software is available on the ultrasound equipment.

In addition, the estimated maximum partial volume reproducibility of 3D-US fell within approximately 10%, corresponding to only \( \pm 3 \text{ mm} \), if volume reproducibility was transferred to diameter reproducibility. On the other hand, compared with volumetric CT assessment, US volume assessment carried some obvious disadvantages. In most cases, it was only possible to establish a partial volume rather than the entire aneurysm volume. Fixed points, except those of maximum contour, could not be obtained, in contrast with CT where the renal arteries and aortic bifurcation can be identified and used as fix points. Finally, the US inter-observer ROV was poorer than the previously reported CT inter-observer ROV.\(^7\)–\(^9\)

The 3D-US centreline diameter was in slightly better agreement with CTA compared with the US dual plane diameter (2.6 mm vs. 1.8 mm). There was, however, no substantial improvement in the ROV between the two methods. The inter-observer ROV for both diameter methods applied in this study was good and comparable with the 3 mm inter-observer ROV recently reported using a standardised ultrasound protocol with ECG gating and off line reading.\(^8\) That study was, however, conducted without paired CT. Hence, the present study is unique in the sense that both the US reproducibility and the inter-modality agreement between US and 3D-CT are reported. In studies comparing the older 2D-US guided diameter measurement and 3D-CT centreline diameter, the mean differences ranged from \(-0.1 \text{ mm} \) to \(7.3 \text{ mm} \), with a SD ranging from 1.8 mm to 7.0 mm.\(^ {10–12} \) In that perspective, the mean inter-modality differences documented in the present study ranging from 1.8 mm to 2.6 mm, and especially a SD ranging from 1.6 mm to 1.7 mm without harming the inter-observer ROV, are indeed satisfactory compared with the older 2D-US performance.

It is, however, important to mention that the present results may have been favoured by the relatively small size of the AAAs included in this series compared with those investigated in the available literature as the present study suggests that the disagreement between paired measurements increased with larger aneurysm size. The finding that image quality and BMI affected neither the inter-modality agreement nor the reproducibility of the diameter assessment should be interpreted with some caution as patients with poor image quality were excluded and the majority of these patients had a BMI >25 kg m\(^{-2} \). The US dual plane diameter was systematically made in peak systole from outer to inner vessel wall, which favours a greater mean US diameter. In contrast, the 3D-US acquisition was obtained without any ECG gating, and the centreline diameter was measured from inner to inner vessel wall, which favours a lower diameter. However, the 3D-US centreline diameter remained the largest US diameter measured, and it is therefore in better agreement with the 3D-CT measurement. Still, the image plane and axis had a better match with 3D-CT using 3D-US acquisition rather than US dual plane imaging.

There was at least a 14 day interval between readings. It was, however, the same operator, who measured CT and 3D-US. Thus, additional measurements performed independently could potentially have increased the validity. Furthermore, implementation of the results may be questionable as the study results were performed in a well recognized expert centre with access to the newest 3D technology.

Contrary to CT, conventional AAA US diameter measurement is only reliable from clearly insonated parts of the aneurysm wall, which explains why the antero-posterior axis is used. This limitation is less marked when 3D-US acquisition is used, as the maximum diameter can be
obtained in any direction equivalent to CT practice. This also includes diameter measurement in the lateral plane, which is especially useful in curved AAA. Moreover, because the 3D-US AAA model is composed of several images, the technique can, to a certain extent, compensate for the less detailed lateral vessel wall and for local suboptimal insonation. On the other hand, a potential source of error in 3D-US acquisitions was the inability to allow ECG gating and thereby improved control of the AAA pulsatility reported to be 1.95 mm on average between end diastole and peak systole. It was not confirmed, however, that the most pulsatile AAA presented a worse outcome for the 3D-US centreline diameter.

According to the guideline of the Society of Vascular Surgery, the optimal method for measuring the aortic diameter is the 3D-CT maximum diameter measured perpendicular to the centreline. In clinical practice, however, conventional ultrasound performed with a curved array is the method of choice for decision making regarding small AAA. US dual plane imaging, 3D-US centreline diameter, and volume assessment all represent new developments with a potential to improve this decision making. Current US examinations of small AAA are hampered by an inter-observer variability ranging from 2 to 10 mm, and it is well accepted that the current US technique has a tendency to underestimate the maximum diameter compared with CT. This may be critical for patients whose maximum diameter is close to the threshold for surgery. The 3D-US derived measures described in the present study seem to improve the agreement with CT and could therefore optimise its future use. Thirteen patients were identified whose maximum diameter was within 5 mm of the threshold for surgery. The 3D-US is not ideal but the present study indicates that at least a quarter of these patients would be correctly referred for surgery.

Based on experience with 3D-US, including the results from this study, US dual plane imaging has been implemented in the authors’ routine AAA US scanning protocol. Presently, the need for off line post-processing is the main reason why the 3D-US centreline diameter modality has not yet been implemented at the authors’ clinic, at which 5–10 AAA examinations are done a day. With further software improvement, the authors are convinced that 3D-US centreline diameter will find its place in the clinical management of small AAA as its reproducibility is good and its agreement with CT even better. Whether partial volume assessment may provide more valuable information on growth than the simple maximum diameter needs further investigations, but the idea seems appealing. However, there is concern regarding the utility of such adjunctive information based on partial volume rather than the total volume. The present technology does not allow estimation of the total volume, although with further development of especially the 3D data acquisitions, there is a remote possibility of encompassing the entire residual sac.

In conclusion, 3D-US significantly improves diameter measurement of small AAA, and US dual plane imaging in particular can be implemented as a routine procedure in a busy vascular laboratory to underpin clinical decision making.

CONFLICT OF INTEREST

HS has received a research grant and honorarium from Philips Ultrasound.

FUNDING

The Danish Heart Foundation, the AP Moeller Foundation, and the Frankel Foundation provided financial support for this research project.

REFERENCES


13 Grondal N, Bramsen MB, Thomsen MD, Rasmussen CB, Lindholt JS. The cardiac cycle is a major contributor to variability in size measurements of abdominal aortic aneurysms by ultrasound. *Eur J Vasc Endovasc Surg* 2011;43:30–3.
