Measurement of Maximum Diameter of Native Abdominal Aortic Aneurysm by Angio-CT: Reproducibility is Better with the Semi-automated Method

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WHAT THIS PAPER ADDS
Computed tomography angiogram (CTA) is the standard for measurement of maximum native abdominal aortic aneurysm (AAA) diameter. Despite precise measurement techniques, diameter may differ significantly between observers. Reproducibility beyond recommended thresholds is frequent. Semi-automated software provides cross sections perpendicular to the lumen centreline, with maximum diameter calculated on the slice of interest. We show that this software may reduce variability. Surgeons must be aware of these limits during management decisions, especially when AAA diameter is close to recommended thresholds for intervention, or when AAA is suspected to grow rapidly on successive CTA, as inaccurate measurement may affect the decision to intervene.

Objectives: We sought to identify the technique yielding the best reproducibility from among various measures of native maximum abdominal aortic aneurysm (AAA) diameter with computed tomography angiography (CTA).

Methods: Ten parameters of maximum diameter in 68 native AAA were measured double-blind by three radiologists on orthogonal planes, curved multiplanar reconstructions, and, finally, using semi-automated software. The semi-automated software creates the AAA lumen centreline and automatically provides cross sections perpendicular to this centreline. The maximum diameter in any direction is automatically calculated once the slice of interest has been selected. Intra- and inter-observer reproducibility and discordance >5 mm were analysed.

Results: Intra-observer reproducibility was high. The limits of agreement were within the clinically accepted range [−5; +5 mm] in 27/30 (90%) comparisons. The method common to all three observers that yielded the lowest values was the semi-automated method. Inter-observer reproducibility was poorer. The limits were outside the clinically accepted range in 26/30 (87%) comparisons. The semi-automated method led to lower intra- (0%) and inter-observer (5.88%) discordances rates.

Conclusion: Even using precise methodology, the reproducibility of maximum diameter measurements of native AAA on CTA may exceed recommended thresholds. The semi-automatic method yielded the lower discordance rates and provided a more relevant anatomical approach for measuring the maximum diameter of an AAA.

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INTRODUCTION
Most decisions regarding the treatment of native abdominal aortic aneurysm (AAA) are based on its absolute maximal diameter and growth rate.

Computed tomography angiography (CTA) is the reference imaging technique performed before intervention. Images can be acquired in several planes for the measurement of maximal AAA diameter. However, there is no consensus regarding the definition of AAA maximum diameter, and the range of measurements possible with CTA offers a wide choice to clinicians. Patient care heavily depends on this parameter, as the thresholds for surgical intervention are precisely defined, namely 50–55 mm in men and a growth rate >10 mm in 1 year.

A criterion of choice to select the best methodology for maximum AAA diameter measurement could be the reproducibility of the measure. Given that the decision for
intervention relies on either the maximum diameter or an accelerated growth rate, errors in measurement between different readers could have a significant effect on patient care.

Various planes for AAA maximum diameter measurement are available in routine clinical practice on CTA, that is, mainly orthogonal planes, and planes obtained after curved multi-planar reconstructions. However, the real maximum diameter is that obtained on cross sections perpendicular to the AAA centreline. Semi-automated softwares have been introduced for this purpose. In our radiology department, we use a three-dimensional (3D) analysis software, which creates the abdominal aortic lumen centreline once the observer has placed two points at the celiac aortic level and the aortic bifurcation, and then the software automatically provides cross sections perpendicular to this centreline. The cross section containing the maximum aortic diameter in any direction perpendicular to the lumen centreline is visually selected by the observer, who then manually draws the outer limits of the AAA, including thrombus and the arterial wall. Then, the maximum diameter in any direction is automatically calculated. In this context, the aim of this study was to analyse the reproducibility of various CTA-based measures of maximum diameter of native AAA, including those obtained with the semi-automated software, and to identify the measurement technique that yields the best reproducibility between three radiologists, with a view to proposing a reference for routine clinical practice.

Figure 1. Flow chart of the computed tomography angiography (CTA) database constitution. Note. AAA = abdominal aortic aneurysm.

**N = 300 patients**

Patients identified with: «aneurysm», «aorta», «abdominal» «male gender» combined with the Boolean operators «AND» and «OR» from the computerized indication for CTA examination.

**After reading the whole indication for CTA examination**

Exclusions: inflammatory aneurysm; false aneurysm; aneurysm after open repair or stent-graft; diameter less than 30mm; thoracic, thoraco-abdominal, and iliac aneurysms. Older CTA selected in case of multiple examinations for the same patient.

**220 patients excluded**

3 = Iliac aneurysm
64 = Thoracic aortic aneurysm
6 = Thoraco-abdominal aortic aneurysm
14 = More than 1 exam
28 = Post-operative follow up
99 = No AAA
2 = Carotid aneurysm
3 = False aneurysm
1 = Subclavian aneurysm

**80 eligible patients**

CTA re-reading
Selection of CTA at arterial phase after contrast injection showing on axial slices an infrarenal AAA with a maximum diameter in any direction greater than or equal to 30 mm

**12 patients excluded**

3 = Iliac aneurysm
1 = Thoracic aortic aneurysm
1 = Thoraco-abdominal aortic aneurysm
1 = Post-operative follow up
6 = Supra-renal AAA

**68 patients included**
Table 1. Definitions and abbreviations of diameters measured in this study.

<table>
<thead>
<tr>
<th>Plane</th>
<th>Diameter</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>Antero-posterior</td>
<td>Axial_APD</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>Axial_TrD</td>
</tr>
<tr>
<td></td>
<td>Maximum in any direction</td>
<td>Axial_Dmax</td>
</tr>
<tr>
<td>Sagittal MPR</td>
<td>Strictly antero-posterior</td>
<td>Sag_APD</td>
</tr>
<tr>
<td></td>
<td>Antero-posterior perpendicular</td>
<td>Sag_PerpD</td>
</tr>
<tr>
<td></td>
<td>to the AAA long axis</td>
<td></td>
</tr>
<tr>
<td>Coronal MPR</td>
<td>Strictly transverse</td>
<td>Coro_TrD</td>
</tr>
<tr>
<td></td>
<td>Transverse perpendicular to the</td>
<td>Coro_PerpD</td>
</tr>
<tr>
<td></td>
<td>AAA long axis</td>
<td></td>
</tr>
<tr>
<td>Curvilinear parasagittal MPR</td>
<td>Antero-posterior perpendicular</td>
<td>PSR_PerpD</td>
</tr>
<tr>
<td></td>
<td>to the AAA long axis</td>
<td></td>
</tr>
<tr>
<td>Curvilinear paracoronal MPR</td>
<td>Transverse perpendicular</td>
<td>PCR_PerpD</td>
</tr>
<tr>
<td></td>
<td>to the AAA long axis</td>
<td></td>
</tr>
<tr>
<td>Semi-automated axial plane</td>
<td>Minimum in any direction</td>
<td>Semi-automated_D</td>
</tr>
<tr>
<td></td>
<td>perpendicular to the lumen</td>
<td></td>
</tr>
<tr>
<td></td>
<td>centreline</td>
<td></td>
</tr>
</tbody>
</table>

Note. MPR = multiplanar reformation; AAA = abdominal aortic aneurysm.

PATIENTS AND METHODS

CTA protocol

Examinations were undertaken on two multidetector CT scanners with the patient in the supine position during a single breath-hold (Somatom Sensation 64 [Siemens, Erlangen, Germany] and Lightspeed 64 [General Electric, Milwaukee, WI, USA]).

The scanning parameters were as follows: slice thickness 0.6–0.625 mm, collimation 0.75–1.5 and field of view ranging from 280 to 320; gantry rotation time 0.42 seconds; tube voltage 120 kV; pitch 0.26.

A bolus of 80 mL of iomeprol, 400 mg I/mL (Iomeron 400; Bracco, Courcouronne, France) was injected intravenously (4 mL/second) via an 18-gauge catheter placed in the antecubital vein followed by 50 mL of saline.

Multiplanar reconstruction (MPR) images of the abdominal aorta were routinely produced in the axial, sagittal, and coronal planes. Curvilinear MPR, perpendicular to this central line, were constructed in the parasagittal and paracoronal planes. Measures were as follows:

1. After selection of the axial slice displaying the largest diameter, the radiologists measured:
   - antero-posterior diameter Axial_APD (Fig. 2A);
   - transverse diameter Axial_TrD (Fig. 2B);
   - maximum diameter in any direction Axial_Dmax (Fig. 2C).

2. After selection of the sagittal and coronal MPR images displaying the largest diameter, the radiologists measured:
   - on sagittal MPR, antero-posterior diameter Sag_APD (Fig. 2D) and diameter perpendicular to the long axis of the aneurysm Sag_PerpD (Fig. 2E);
   - on coronal MPR, transverse diameter Coro_TrD (Fig. 2F) and diameter perpendicular to the long axis of the aneurysm Coro_PerpD (Fig. 2G).

3. Using dedicated software (3D Voxel 6.3.2 Workstation; Toshiba Medical Visualization System Europe, Edinburgh, UK), a central lumen line was drawn manually through the lumen of the aorta by positioning points in the centre of the lumen in the axial, sagittal, and coronal planes. Curvilinear MPR, perpendicular to this central line, were constructed in the parasagittal and paracoronal planes. Measures were as follows:
   - on parasagittal reformatted images, antero-posterior diameter perpendicular to the long axis of the aneurysm PSR_PerpD (Fig. 2H);
   - on paracoronal reformatted images, transverse diameter perpendicular to the long axis of the aneurysm PCR_PerpD (Fig. 2I).

Second, using dedicated 3D analysis software (Advanced Vessel Analysis Xpress; General Electric, Milwaukee, WI, USA), the maximum diameter perpendicular to the centerline Semi-automated_D was measured semi-automatically (step 4). The centerline was automatically defined once the observer had placed two points in the centre of the aortic lumen, one above the renal arteries and the second at the aortic bifurcation (Fig. 3). Two reconstructions were produced: cross sections of the AAA perpendicular to the lumen centreline, and sections showing a longitudinal view of the aorta. A contour of the aortic lumen was automatically produced on the cross sections (Fig. 4A). The observer study was approved by the Institutional Review Board of Reims University Hospital, France.

CTA analysis

Diameters were measured from the outside to outside wall of the aneurysm using electronic callipers with a zoom function.

Ten measurements of the maximum AAA diameter were performed (Table 1). The slices of interest displaying the largest aneurysm diameter were selected by each observer (although the slice numbers were not recorded).

First, nine measurements were performed on the PACS workstation, as follows.

1. After selection of the axial slice displaying the largest diameter, the radiologists measured:
   - antero-posterior diameter Axial_APD (Fig. 2A);
   - transverse diameter Axial_TrD (Fig. 2B);
   - maximum diameter in any direction Axial_Dmax (Fig. 2C).

2. After selection of the sagittal and coronal MPR images displaying the largest diameter, the radiologists measured:
   - on sagittal MPR, antero-posterior diameter Sag_APD (Fig. 2D) and diameter perpendicular to the long axis of the aneurysm Sag_PerpD (Fig. 2E);
   - on coronal MPR, transverse diameter Coro_TrD (Fig. 2F) and diameter perpendicular to the long axis of the aneurysm Coro_PerpD (Fig. 2G).

3. Using dedicated software (3D Voxel 6.3.2 Workstation; Toshiba Medical Visualization System Europe, Edinburgh, UK), a central lumen line was drawn manually through the lumen of the aorta by positioning points in the centre of the lumen in the axial, sagittal, and coronal planes. Curvilinear MPR, perpendicular to this central line, were constructed in the parasagittal and paracoronal planes. Measures were as follows:
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visually selected the cross section perpendicular to the centreline containing the maximum diameter in any direction, and manually corrected the lumen boundary with a freehand drawing tool, where necessary, to include the thrombus and the wall of the aneurysm (Fig. 4B).

Three observers—namely one junior resident (J) and one vascular interventional radiologist (R) with, respectively, 3 and 20 years of experience, and a specialist in vascular medicine with more than 15 years of experience in vascular radiology (V), who were all blinded to previous radiological reports—individually measured maximum AAA diameter on each examination.

Each observer performed two readings, at a minimum of a 4-week interval, yielding six series of measures:

- junior readings 1 (J1) and 2 (J2);
- senior readings 1 (S1) and 2 (S2);
- vascular readings 1 (V1) and 2 (V2).

As the slice number of the first reading had not been recorded, each observer had to reselect the slices of interest at the second reading. When results were discordant, no additional reading was performed as a consensus on the diameter value was not required for the purposes of this study.

**Statistical analysis**

Data are described as mean and SD for quantitative variables and number (percentage) for qualitative variables.

Comparisons between diameter values from the first reading of all observers (J1, S1, and V1) were performed using the paired Student t test.

Intra-observer reproducibility (J1 vs. J2, S1 vs. S2, V1 vs. V2) and inter-observer reproducibility (J1 vs. S1, J1 vs. V1, S1 vs. V1) were evaluated using the intra-class correlation coefficient (ICC) and the Bland—Altman method.

The Bland—Altman method provides (1) the mean value of the paired differences, (2) the coefficient of repeatability, which is defined as $1.96 \times SD$ of the differences, and (3) the limits of agreement (LOA) equal to $\text{mean} \pm 1.96 \text{SD}$. When applied to AAA diameter analysis, the clinical threshold was 5 mm for the coefficient of repeatability, and the clinically accepted range was $[-5 \text{ mm}; +5 \text{ mm}]$ for the LOA.

For each AAA and for each diameter, the absolute difference in diameter values between J1 and J2, S1 and S2, V1...
and V2, J1 and S1, J1 and V1, S1 and V1 was calculated. For each diameter, the number of differences ≤ 5 mm, between 5 mm and 10 mm, and ≥ 10 mm were recorded. Parameters that were significantly less frequently discordant were identified using the chi-square or Fisher exact tests, as appropriate.

A p-value < .05 was considered statistically significant. All analyses were performed using SAS version 9.0 (SAS, Cary, NC, USA).

RESULTS

CTA database

In total, 68 patients (corresponding to 68 CTA), were included in the study (Fig. 1). The mean age was 72 ± 10 years. All CTA were of good quality and none was excluded because of artefacts or movement. The presence of calcifications did not affect the measurements because each diameter measured was the external diameter.

The comparisons of the mean diameters noted by the three observers on the first reading are reported in Table 2. The mean diameters did not differ significantly between observers.

Intra-observer reproducibility

Intra-observer reproducibility assessed with the Bland–Altman method is reported in Table 3. Regarding the readings by the junior observer, the lowest coefficient of repeatability was 1.99 mm, and this value was obtained for the measure of the curved MPR sagittal plane. All the LOA were within the acceptable limits of [−5 mm; +5 mm].

Regarding the readings by the senior observer, the lowest coefficient of repeatability was 0.68 mm, and this was obtained with the semi-automated method, which also provided the lowest LOA [−0.70; 0.67].

Regarding the readings by the vascular observer, the lowest coefficient of repeatability was 1.87 mm, and this value was obtained for the maximum diameter in any direction on axial planes. All the LOA were within the acceptable limits of [−5 mm; +5 mm].

For all observers, the coefficients of repeatability obtained with the semi-automated method were low and the corresponding LOA were within the acceptable limits of 5 mm; +5 mm].

Overall, the LOA were within the clinically accepted range for 27/30 (90%) comparisons.

The Bland–Altman plot of the differences showed no visible relationship between the differences in measures and the size of the AAA (Fig. 5A–C). All other Bland–Altman plots are available as Supplementary materials.

Inter-observer reproducibility

The inter-observer reproducibility, as assessed by the ICC, was high for all operators, with an ICC (95% confidence interval [CI]) ranging from 0.965 (0.948–0.977) to 0.996 (0.995–0.997) (see Supplementary Table S1).
Inter-observer reproducibility assessed with the Bland—Altman method is reported in Table 4 and illustrated in Fig. 5(D–F).

The lowest coefficient of repeatability observed for the comparisons between first readings was obtained with the maximum diameter in any direction measured on the axial plane (3.83, 3.08, and 4.29). The LOA were outside the limits of clinical acceptance of [−5 mm; +5 mm] for all diameters between J1 and S1, and between S1 and V1, and were within the acceptable limits only for four diameters between J1 and V1. Overall, the LOA was outside the clinically accepted range for 26/30 (87%) comparisons.

With the semi-automated method, the LOA were within the clinically acceptable limits for J1 versus V1 only.

The Bland—Altman plot showed no visible relationship between the differences in measures and the size of the AAA (Fig. 5D–F). All other Bland—Altman plots are available as Supplementary material.

**Table 2.** Comparison between diameter values obtained from the first reading of both observers (J1, S1, V1).

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Reading J1</th>
<th>Reading S1</th>
<th>Reading V1</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 68</td>
<td>n = 68</td>
<td>n = 68</td>
<td></td>
</tr>
<tr>
<td>Axial_APD</td>
<td>47.4 ± 11.0</td>
<td>46.8 ± 11.0</td>
<td>49 ± 11</td>
<td>.46</td>
</tr>
<tr>
<td>Axial_TrD</td>
<td>48.44 ± 11.00</td>
<td>47.6 ± 11.0</td>
<td>49.1 ± 11.0</td>
<td>.72</td>
</tr>
<tr>
<td>Axial_Dmax</td>
<td>52.6 ± 11.0</td>
<td>50.4 ± 11.0</td>
<td>52.4 ± 11.0</td>
<td>.49</td>
</tr>
<tr>
<td>Sag_APD</td>
<td>48.3 ± 11.0</td>
<td>46.2 ± 11.0</td>
<td>49.1 ± 11.0</td>
<td>.29</td>
</tr>
<tr>
<td>Sag_PerpD</td>
<td>47.9 ± 11.0</td>
<td>45.8 ± 11.0</td>
<td>48.9 ± 11.0</td>
<td>.25</td>
</tr>
<tr>
<td>Coro_TrD</td>
<td>48.9 ± 11.0</td>
<td>47 ± 11</td>
<td>49.5 ± 11.0</td>
<td>.42</td>
</tr>
<tr>
<td>Coro_PerpD</td>
<td>48.4 ± 11.0</td>
<td>45.9 ± 11.0</td>
<td>48.8 ± 11.0</td>
<td>.24</td>
</tr>
<tr>
<td>PSR_PerpD</td>
<td>47.5 ± 11.0</td>
<td>45.8 ± 11.0</td>
<td>48.6 ± 11.0</td>
<td>.29</td>
</tr>
<tr>
<td>PCR_PerpD</td>
<td>48.3 ± 11.0</td>
<td>46.6 ± 11.0</td>
<td>49.4 ± 11.0</td>
<td>.33</td>
</tr>
<tr>
<td>Semi-automated_D</td>
<td>50.7 ± 11.0</td>
<td>50.3 ± 12.0</td>
<td>50.7 ± 11.0</td>
<td>.97</td>
</tr>
</tbody>
</table>

**Note.** Diameters are expressed in mm as mean ± SD. PSR/PCR = parasagittal/paracoronal reformation.

*For diameter abbreviations, see Table 1.*

**Discordance**

For the evaluation of intra-observer discordance, 68 pairs of values were available for each of the ten parameters measured, for each of the three comparisons (i.e., J2–J1; S2–S1; V2–V1).

For the evaluation of inter-observer discordance, 68 pairs of values were available for each of the ten parameters measured, for each of the three comparisons (i.e., J1–S1; J1–V1; S1–V1).

The percentage of discordances in each category (≤5 mm, 5–10 mm, >10 mm) are shown in Tables 5 and 6.

**Intra-observer discordance.** With the semi-automated method, all the intra-observer discordances were ≤5 mm. Intra-observer discordance >10 mm for the junior observer was observed for only one patient in the transverse diameter perpendicular to the long axis of the AAA on the coronal plane (Coro_PerpD). Intra-observer discordance >10 mm for the senior observer was observed for only one patient, but in three different planes. Intra-observer discordance >10 mm for the vascular observer was observed for only one patient in the transverse diameter perpendicular to the long axis of the AAA on the coronal plane (Coro_PerpD). The discordances were observed on three different AAA, all of which were sinuous with asymmetric intrasaccular thrombus.

There was no significant difference in the percentage of differences >5 mm between J1 and J2, between S1 and S2, or between V1 and V2 for all parameters (p = .96, p = .65, and p = .83 respectively).

**Inter-observer discordance.** We observed inter-observer discordance of ≥10 mm for 32 measures, from eight patients (Table 6). One AAA had two successive dilations with close visual dimensions, and thus it is possible that the analyses were not performed on the same dilation. The seven other AAAs were sinuous and had asymmetric intrasaccular thrombus. Three of the eight AAAs were also responsible for the intra-observer discordance reported above.
With the semi-automated method, 5.88% of the differences between observers were >5 mm.

The lowest discordance rate (0%) was obtained between J1 and V1 with the maximum diameter in any direction on the axial plane. Regarding J1–S1, the semi-automated method yielded a statistically lower percentage of discordance >5 mm as compared with the transverse diameter perpendicular to the long axis of the AAA on coronal plane (5.88% vs. 17.65%, Table 3.

**Table 3.** Intra-observer (J1 vs. J2, S1 vs. S2, and V1 vs. V2) reproducibility assessed by the Bland–Altman method.a

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Junior J1–J2</th>
<th>Senior S1–S2</th>
<th>Vasc V1–V2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial_APD</td>
<td>−0.64 1.55 3.05 −3.69 2.41 0.01 2.17 4.25 −4.24 4.26 −0.05 1.22 2.44 −2.49 2.39</td>
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<td></td>
</tr>
<tr>
<td>Axial_TrD</td>
<td>−0.56 1.61 3.15 −3.71 2.58 −0.09 1.89 3.71 −3.80 3.62 0.27 1.58 3.16 −2.89 3.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial_Dmax</td>
<td>−0.44 1.44 2.83 −3.27 2.39 0.18 1.80 3.52 −3.35 3.70 0.02 0.93 1.87 −1.85 1.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sag_APD</td>
<td>−0.34 1.54 3.02 −3.36 2.68 −0.53 1.97 3.86 −4.39 3.33 0.12 1.21 2.43 −2.30 2.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sag_PerPD</td>
<td>−0.11 1.75 3.43 −3.54 3.32 −0.31 2.32 4.56 −4.87 4.24 0.28 1.33 2.67 −2.38 2.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coro_TrD</td>
<td>−0.35 1.84 3.60 −3.96 3.25 −0.65 2.96 5.80 −6.44 5.15 0.01 1.30 2.60 −2.59 2.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coro_PerPD</td>
<td>0.03 2.11 4.13 −4.10 4.16 −0.98 2.74 5.37 −6.34 4.39 −0.08 1.77 3.53 −3.61 3.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSR_PerPD</td>
<td>0.07 1.01 1.99 −1.91 2.06 −0.69 2.47 4.84 −5.53 4.15 0.02 1.4 2.80 −2.79 2.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCR_PerPD</td>
<td>0.31 1.72 3.37 −3.06 3.67 −0.15 2.33 4.56 −4.71 4.41 0.39 1.38 2.76 −2.36 3.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-automated_D</td>
<td>0.44 1.24 2.44 −2.00 2.88 −0.01 0.35 0.68 −0.70 0.67 0.09 1.08 2.16 −2.07 2.24</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. Overall, the limits of agreement were within the clinically accepted range [−5; +5 mm] in 27/30 (90%) comparisons. CR = coefficient of repeatability; LOA = limits of agreement; PSR/PCR: parasagittal/paracoronal reformation.

a Mean of differences, coefficient of repeatability (1.96 SD) and the limits of agreement [mean −1.96 SD; mean +1.96 SD] are reported.

b For diameter abbreviations, see Table 1.

Figure 5. The Bland–Altman plot of the differences with the semi-automated method. No visible relationship between the differences in measures and the size of the AAA was present.

Note. A = junior intra-observer reproducibility; B = senior intra-observer reproducibility; C = vascular intra-observer reproducibility; D = inter-observer reproducibility (junior vs. senior); E = inter-observer reproducibility (junior vs. vascular); F = inter-observer reproducibility (senior vs. vascular).
p = .03). Compared with the semi-automated method, all other results were not statistically significant.

Regarding J1–V1, the percentage of discordance >5 mm ranged between 0 and 5.88%, and did not differ significantly between diameters.

Regarding S1–V1, the percentage of discordance >5 mm ranged between 5.88% and 19.11%. There was a significant difference between the semi-automated method and the following diameters: transverse diameter perpendicular to the AAA long axis on coronal plane (p = .02), anteroposterior diameter perpendicular to the AAA long axis on curvilinear para-sagittal MPR (p = .03) and transverse diameter perpendicular to the AAA long axis on curvilinear para-coronal MPR (p = .02).

Table 4. Inter-observer (J1 vs. S1, J1 vs. V1, and S1 vs. V1) reproducibility assessed by the Bland–Altman method.a

<table>
<thead>
<tr>
<th>Diameter</th>
<th>J1–S1</th>
<th></th>
<th></th>
<th></th>
<th>J1–V1</th>
<th></th>
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<tr>
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<td>SD</td>
<td>CR</td>
<td>LOA</td>
<td>Mean (mm)</td>
<td>SD</td>
<td>CR</td>
<td>LOA</td>
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<td>CR</td>
<td>LOA</td>
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<td>6.50</td>
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<td>−1.63</td>
<td>1.91</td>
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<td>−0.35</td>
<td>3.29</td>
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</table>

Note. Overall, the limits of agreement were outside the clinically accepted range [−5; +5 mm] in 26/30 (87%) comparisons. CR = coefficient of repeatability; LOA = limits of agreement; PSR/PCR = parasagittal/paracoronal reformation.

a Mean of differences, coefficient of repeatability (1.96 SD) and the limits of agreement [mean −1.96 SD; mean +1.96 SD] are reported.

b For diameter abbreviations, see Table 1.
DISCUSSION

Our study shows that inter-observer reproducibility in measuring AAA was poor. The maximum diameter in any direction measured on the axial plane provided the lowest coefficient of repeatability, but the LOA were outside the clinically accepted range, except for four pairs of comparisons. Conversely, intra-observer reproducibility was higher: the LOA were within the clinically accepted range for 27/30 comparisons. The method that yielded the best results was the semi-automated method, which showed the lowest rates of intra- (0%) and inter-observer (5.88%) discordance >5 mm; all the LOA were within the clinically accepted range regarding intra-observer reproducibility, whereas 2/3 comparisons were unsatisfactory with inter-observer reproducibility values outside the LOA.

CTA is considered as the technique of reference for measuring the maximum diameter of native AAA when surgery is being considered. However, CTA images yield a wide range of possible measures, particularly when several planes are available. Native axial slices, coronal, and sagittal planes are based on an anatomical reference point. Curvilinear MPR and semi-automated methods use the aorta as a reference, leading to a more realistic representation of AAA anatomy, and, consequently, the maximum diameter estimated with these approaches is closer to the real diameter.

Patients with native AAA who are being considered as candidates for surgery are often seen by several physicians during the work-up, and the CTA may be analysed by several different clinicians during the decision-making process. Therefore, the reproducibility of the measurement is of paramount importance in order to guarantee that the therapeutic best decision is made (i.e., intervention or follow-up), and choosing the parameter that offers the best reproducibility appears logical in the context of multiple interpretations of the same images during management.

Several studies have focused on intra- and inter-observer reproducibility of maximum diameter measurement in native AAA with CTA.\textsuperscript{2,4,7,10,13} However, the methodology and statistical approaches varied between studies, thereby precluding direct comparison with our study. One difference was the various number of observers. Also, the parameters used as variables in the statistical analysis differed from one study to another, making comparison of findings difficult.

Nonetheless, intra-observer reproducibility was shown to be superior to inter-observer reproducibility,\textsuperscript{7,10} and our findings are in line with this. However, the diameter yielding the highest reproducibility differed from one study to another.

Two different CT machines were used in this study, as may often be the case in real-life clinical practice during patient follow-up. However, both machines used here were 64-slice multidetector CT scanners, with comparable slice thickness (0.6 and 0.625 mm) and providing similar performance in terms of vascular imaging. However, we did not specifically analyse the reproducibility of one CT machine to the other.

There is currently no consensual methodology for the measurement of maximum AAA diameter, but standardisation

<table>
<thead>
<tr>
<th>Plane</th>
<th>Native axial plane and sagittal and coronal planes</th>
<th>Curvilinear MPR</th>
<th>Semi-automated method</th>
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<td>Axial_ APD</td>
<td>Axial_ TrD</td>
<td>Axial_ Dmax</td>
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<td>J1—J2</td>
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<td>67</td>
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<tr>
<td>&gt;5 mm</td>
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<tr>
<td>Percentage of discordances &gt;5 mm</td>
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<tr>
<td>S1—S2</td>
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<td>67</td>
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<td>Percentage of discordances &gt;5 mm</td>
<td>1.47%</td>
<td>1.47%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Note. MPR = multiplanar reconstruction; PSR/PCR = parasagittal/paracoronal reformation.

\textsuperscript{a} For diameter abbreviations, see Table 1.
is mandatory, as it has been shown to be an important factor in improving reproducibility.\(^\text{13}\) Although our study was based on a specific standardised protocol, which yielded clinically acceptable intra-observer reproducibility (27/30 comparisons with LOA within the clinical acceptable limits), the quality of the inter-observer reproducibility was lower, reflecting real-life clinical practice. Lederle et al.\(^\text{10}\) also suggested that, in order to limit variability, one possibility would be to limit the number of radiologists who measure AAA, and advocated seeking agreement between surgeons and radiologists on a precise definition of AAA diameter.

Even with the use of standardised measuring processes, successive steps still require human intervention. First, on native axial slices, sagittal, and coronal planes, the radiologist visually selects the slice containing the largest section of the AAA. Determining the maximum diameter in the axial slices, and the maximum diameter perpendicular to the centreline in the sagittal or coronal planes, relies on a subjective choice of the axis of measurement. According to Abada et al.,\(^\text{12}\) when the observers themselves selected the axial slices to be measured (a situation close to the conditions of real-life clinical practice), the variability was greater than when the slices were preselected. This is because, when left to choose themselves, the observers disagreed on the choice of slice in most cases. One limitation of our study is that diameter measurements were performed on unselected slices. However, slice number is not systematically recorded in clinical routine. Second, to create a curvilinear MPR, the radiologist must place a succession of points in the middle of the AAA in the sagittal or coronal plane, in order to delineate the AAA centreline. Once the curvilinear MPRs are obtained, the section of AAA containing the maximum diameter and the axis of measurement perpendicular to the centreline are both visually determined. Again, Abada et al.\(^\text{12}\) found that variability was substantial with free MPR measurements, probably resulting from AAA reconstructions that the radiologists had created themselves, and which were therefore different.

Advanced post-processing software programs can semi-automatically generate the centreline from the enhanced aortic lumen\(^\text{8}\) and provide cross sections perpendicular to the lumen centreline. In our experience, although human intervention is reduced, the radiologist still had to (1) place two points in the centre of the aortic lumen; (2) determine the slice containing the largest cross section of the AAA on the reformatted slices perpendicular to the lumen centreline; and (3) draw the outer limits of the AAA including thrombus and arterial wall. Only after these parameters were defined by the radiologist could the software automatically calculate diameters on the selected slice.

Several studies have reported that software providing planes perpendicular the lumen centreline makes it possible to increase the reproducibility of the measurement.\(^\text{1,7}\) Our results are only partially in accordance with these conclusions. With the semi-automated method, the mean diameters did not statistically differ between observers in our study. Indeed, the semi-automated method was the technique common to all observers with the best intra-observer reliability. Regarding inter-observer reproducibility,
comparison between J1 and V1 led to the highest rate of reproducibility, with four diameters associated with LOA within the limits, including those obtained with the semi-automated method. For J1 versus S1, and S1 versus V1, results obtained with the semi-automated method were outside the $[-5 \text{ mm}; +5 \text{ mm}]$ limits. Finally the percentage of discordance $>5 \text{ mm}$ was low, at 0% for intra-observer and 5.88% for inter-observer comparisons.

Using analysis of discordance, we also found that discordances $>10 \text{ mm}$ mostly occurred in measurements from AAA with considerable angulation and asymmetric thrombus. Furthermore, we found that with the semi-automated method, the rates of discordance $>10 \text{ mm}$ were low (between 0 and 2.94%). One potential avenue for future research towards improving reproducibility might be to develop a fully-automated measurement technique. Indeed, a program that automatically selects the cross section with the maximum diameter would be of infinite value. This software should provide the outer walls of the AAA, and not the lumen boundaries, as used in the present study. However, for the moment, to the best of our knowledge, such software is, unfortunately, not available in clinical practice.

AAA is a 3D disease, which, until now, has generally been characterised by its maximum diameter. The real maximum diameter is that obtained from cross sections perpendicular to the AAA centreline in any direction. Native axial slices are directly available, while strict antero-posterior and transverse diameters are commonly performed, but may not correspond to the maximum diameter when AAA is tortuous. In addition, the maximum diameter in any direction is overestimated when the AAA is tortuous. Both these situations can lead to erroneous decisions for subsequent patient care. Sagittal and coronal planes provide an elongated view of the AAA, but are not aligned to the AAA centreline. Curvilinear MPR are commonly used to measure the maximum diameter perpendicular to the centreline, but these techniques are time consuming. Furthermore, as previous studies reported no improvement in reproducibility, they were not recommended in routine clinical practice. In our study, curvilinear MPR was not inferior to other parameters, based on the Bland–Altman analysis. Although the results obtained with the semi-automated method were somewhat disappointing, the analysis of discordance leads us, nonetheless, to recommend its use at present over other protocols.

Semi-automatic generation of the centreline by most software programs usually corresponds to the AAA lumen centreline, as it follows the path of the contrast medium in the aortic lumen. The software we used in this study also created the lumen centreline. However, the AAA lumen centreline may differ from the actual centreline if the thrombus is asymmetrical, therefore leading to inaccurate aneurysmal cross sections. An AAA centreline based on the outer walls of the AAA has recently been proposed for the calculation of both automated maximum diameter and AAA volume. Kauffmann et al. reported excellent intra-observer reproducibility with this software, and a close correlation between values obtained with the software and the double-oblique method.

CONCLUSION

Even when using a precise methodology for the measurement of native AAA diameter on CTA, significantly different values for the same parameter may be obtained between observers, and intra- and inter-observer reproducibility outside the recommended thresholds is not uncommon. This should be taken into account during management decisions, when AAA diameter is close to recommended clinical thresholds for repair, or when AAA is suspected of growing too rapidly on successive CTAs. Inaccurate measurements could affect the decision to intervene, and thus have substantial repercussions for the patient. Minimising the variability in AAA diameter measurement requires a consensual methodology for measurement based on a reproducible method. Efforts to reduce this variability could include use of semi-automated software. In our experience, semi-automatic measurements showed a clinically acceptable reproducibility, and were closer to reality for oblique AAA.

The choice between the lumen or the outer wall centreline remains a subject of debate. Future avenues of research could investigate volumetric evaluation of AAA.

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CONFLICT OF INTEREST

None.

FUNDING

None.

APPENDIX A. SUPPLEMENTARY MATERIAL

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.ejvs.2013.10.013.

REFERENCES


