Reproducibility of Deriving Parameters of AAA Rupture Risk From Patient-Specific 3D Finite Element Models

Alexander Hyhlik-Dürr, MD; Tim Krieger; Philipp Geisbüsch, MD; Drosos Kotelis, MD; Thomas Able, MD; and Dittmar Böckler, MD, PhD

Department of Vascular and Endovascular Surgery, Ruprecht-Karls University Heidelberg, Germany.

Purpose: To assess the reproducibility of estimating biomechanical parameters of abdominal aortic aneurysms (AAA) based on finite element (FE) computations derived from a commercially available, semiautomatic vascular analyzer that reconstructs computed tomographic angiography (CTA) data into FE models.
Methods: The CTA data from 10 consecutive male patients (mean age 74 years, range 63–87) with a fusiform infrarenal AAA >5 cm in diameter were used for this study, along with the CTA scans from 4 individuals without aortic disease. Three different observers used semiautomatic reconstruction software to create deformable contour models from axial CT scans. These 3-dimensional FE models captured the aortic wall and thrombus tissue using isotropic finite strain constitutive modeling. Geometric (maximum diameter and volume measurements based on an anatomical centerline) and biomechanical determinants [aneurysm peak wall stress (PWS) and the peak wall rupture risk (PWRR) index] were then calculated from the FE models. The determinations were made 5 times for each anonymized dataset presented for analysis in random order (5-fold measurements for 14 datasets produced 210 measurements from the 3 observers). Inter- and intraobserver variability were assessed by calculating the coefficient of variation of these repeated measures. The methodological variations were expressed with the intraclass correlation coefficient (ICC) and Bland-Altman plots.
Results: The median segmentation time was <1 hour (mean 39.2 minutes, range 25–48) for datasets from the AAA patients; for the healthy individuals, segmentation times were considerably shorter (median 8.7 minutes, range 4–15). Intraobserver reproducibility was high, as represented by a CV <3% for the diameter measurement and <5.5% for volume, PWS, and the PWRR index. The ICC was 0.97 (range 0.95–0.98) for diameter and 0.98 (range 0.97–0.99) for volume; for PWS and the PWRR index, the ICCs were equal at 0.98 (range 0.97–0.99).
Conclusion: The reproducibility of volume and maximum diameter measurements in infrarenal AAAs with FE analysis is high. With the model used in this semiautomatic reconstruction software, wall stress analysis can be achieved with high agreement among observers and in serial measurements by a single observer.

Key words: abdominal aortic aneurysm, finite element model, aneurysm diameter, aortic volume, peak wall stress, rupture risk, reproducibility, computed tomographic angiography

The authors have no commercial, proprietary, or financial interest in any products or companies described in this article.

Address for correspondence and reprints: Alexander Hyhlik-Dürr, MD, Department of Vascular and Endovascular Surgery, Ruprecht-Karls University Heidelberg, Im Neuenheimer Feld 110, 69120 Heidelberg, Germany. E-mail: *alexander.duerr@med.uni-heidelberg.de*

The indication for treatment of asymptomatic abdominal aortic aneurysms (AAAs) is currently based mainly on maximum aneurysm diameter (>5.5 cm), which is used to predict the risk of aneurysm rupture. However, additional factors, such as aneurysm morphology and wall conditions, may contribute to the individual rupture risk. Some authors have therefore concluded that diameter measurements based on axial ultrasound or computed tomographic angiography (CTA) scans may not be reliable parameters for treatment selection.[1,2]

Aneurysm rupture theoretically occurs as aortic wall stress exceeds aortic wall strength. Hence, peak aortic wall stress could offer an additional valid parameter to predict aneurysm rupture.[3] Finite element (FE) models are mathematical constructs that can be used to calculate PWS,[4] which has, along with the calculated peak wall rupture risk (PWRR) index, been positively correlated with aortic diameter and intraluminal thrombus volume.[3] In studies comparing different FE models that included intraluminal thrombus and assumed non-uniform aortic wall thickness, the PWRR index [range between 0.30 (low risk of rupture) and 2.78 (high risk of rupture)] was shown to reinforce PWS as a biomechanical rupture risk index.[3] Therefore, the PWRR index could offer an additional diagnostic tool, more sensitive than diameter estimations from serial CTA imaging.[5–8]

At present, several technical aspects limit the broader application of FE analysis in clinical research and practice, including the time required for the typically manual segmentation process (2–4 hours per patient). Manual segmentation leads to high operator variability in most FE models[4] and could be improved by a robust semiautomatic reconstruction concept. Software is now commercially available to semiautomatically reconstruct computed tomographic angiography (CTA) data into FE models. The reconstruction software allows measurement of 3-dimensional (3D) aneurysm volumes and maximum aneurysm diameters based on an anatomical aortic centerline rather than the contrast-defined centerline of flow technique used in today's common CTA postprocessing software. Lumen-based diameter measurements of tortuous aneurysms with thick and irregular thrombus might be erroneous, so an anatomical centerline should allow more accurate quantification of aneurysm volume and diameter changes than ultrasound or CTA during longitudinal follow-up.

In this evaluation, we sought to determine the reproducibility of measuring aneurysm diameter and volume and calculating PWS in healthy individuals and AAA patients based on >200 3D FE models generated by this semiautomatic vascular analyzer.

METHODS

Patient Cohort

CTA data from 10 consecutive male patients (mean age 74 years, range 63–87) with a fusiform infrarenal AAA >5 cm in diameter were used for this study. Patient characteristics are given in Table 1. For further validation, CTA scans from 4 individuals without aortic disease were also included. The scans of the abdominal aorta were acquired with a 64-slice CT scanner (Somatom Definition; Siemens, Munich, Germany) using standard parameters (in plane resolution 0.33 mm, slice thickness 0.7–1.0 mm) after intravenous injection of a 125-mL bolus of iodated contrast (Ultravist 370; Berlex Laboratories, Wayne, NJ, USA). Brachial systolic blood pressure was recorded according to Riva-Rocci et al.[9] for all patients prior to, during, and directly after CTA data acquisition.

Finite Element Model

Specific aortic geometries were analyzed using a commercially available, semiautomatic vascular analyzer (A4research; VASCOPS GmbH, Graz, Austria) that provides estimates of biomechanical diagnostic parameters of AAAs based on FE computations. Axial and sagittal CTA data were imported into the analyzer, which then reconstructed an active 3D contour model of the aorta from the CTA data. The nodes of the FE model were fixed proximally at the renal arteries and distally at the aortic bifurcation. The elastic properties of the AAA wall and the intraluminal thrombus were described by isotropic models,[3] which

TABLE 1
Characteristics of the 10 Study Patients

Age, y	74 (63–87)
Men	10
ASA classification	3 (3–4)
Hypertension	9
Smoking history	4
Hyperlipidemia	6
COPD	2
Renal insufficiency	2
Coronary artery disease	6
Previous myocardial infarction	3
Previous cardiac surgery / coronary intervention	5

Continuous data are presented as median (range); categorical data are given as counts.
ASA: American Society of Anesthesiologists, COPD: chronic obstructive pulmonary disease.

assume that the tissue's mechanical properties do not depend on the orientation, i.e., the stress-strain responses of circumferential and longitudinal strips of tissue are identical. A reasonably fine mesh was used in the models, which had an expected numerical error of $<5\%$. Uniform arterial blood pressure (120/80 mmHg) and patient-specific blood pressure values were entered into the analyzer to generate the FE models. The aortic centerline was defined as the anatomical midline across the diameter of the entire aneurysm as opposed to a centerline of the contrasted intraluminal space. Details regarding the image segmentation process have been reported.[10] Data analysis was performed on a standard personal computer.

Measurements and Observers

Three independent observers from the department of vascular surgery were trained to use the A4research vascular analyzer program by a tutor in a single session (the training dataset was not included in the study). After the training session, each operator reconstructed and subsequently independently analyzed each FE model from the anonymized CTA data of the 10 AAA patients and 4 healthy individuals, estimating the maximum diameters and volumes and calculating the PWS. The PWRR index was computed in this model by element-wise calculation of von Mises Cauchy stress related to strength in the AAA datasets.[10] A random generator selected the datasets for the observers to assess; the estimates were made 5 times for each dataset (210 models produced from 5-fold determinations for 14 datasets by 3 observers) at varying times over a 3-month period. The time required for reconstructing, processing, and analyzing the study parameters was documented per dataset.

Statistical Analysis

As the reliability of a method in a cross-sectional study depends on the reproducibility of the method and on the variability of the parameter in the population, the methodological variation was related to the biological variability by calculating the intraclass correlation coefficient (ICC) on the basis of an analysis of variance.[11] The ICC has a range from 0 to 1, the latter representing high reliability.

Intraobserver variability was expressed by calculating the mean of the arithmetic differences of the repeated measurements (the 5-fold determinations for each of the 10 AAAs and 4 normal aortas) according to Bland and Altman.[12] Variability was calculated as ± 1.96 standard deviations (SD) of the mean differences; assuming a normal (Gaussian) distribution, 95% of the differences would be expected within this interval. Intraobserver reproducibility of the 4 study variables was also assessed by calculating the coefficient of variation (CV = SD/mean $\times$ 100).

Data analyses were performed using MedCalc (version 10; MedCalc, Mariakerke, Belgium); OriginPro 8 (Origin International Inc., Markham, Ontario, Canada); and Excel (Microsoft Deutschland GmbH, Unterschleißheim, Germany).

RESULTS

Data Acquisition

The median segmentation time (from the beginning of the segmentation process to the time assessment of the study parameters began) was <1 hour (mean 39.2 minutes, range 25–48) for datasets from the patient

cohort; for the healthy individuals, segmentation times were considerably shorter (median 8.7 minutes, range 4–15).

Study Parameters

For normal aortas, the maximum diameter ranged from 16.1 to 16.6 mm and the aortic volumes from 14 to 15 mL. PWS measurements varied between 53 and 55 kPa. For the aneurysmal aortas (Table 2), the maximum aneurysm diameter calculated using centerline measurements ranged from 50.4 to 71.5 mm (mean 60.7). Compared to conventional diameter measurement on the axial CTA, the diameter based on FE analysis was greater in 6 patients (range 2–6 mm) and smaller in 4 (range 1–2 mm). The aneurysm volumes ranged between 92 to 312 mL (mean 192), and the maximal PWS ranged from 163 to 300 kPA (mean 198). The PWRR index in the 10 nonruptured AAAs was <1.0 in all cases (median 0.44, range 0.31– 0.74).

Reproducibility

In nonaneurysmal aortas, the reproducibility of diameter measurements as reflected by the CVs varied between 2.5% and 4.9% for the 5 repeated measurements from each CTA dataset. Abdominal aortic volumes were measured in the healthy cohort with an intraobserver reproducibility of 5.8% to 11.5%, while the CVs for the PWS calculations varied from 3% to 13%. Thus, intraobserver variation was $<10\%$ for diameter, volume, and PWS estimates in individuals without aortic aneurysm.

In the AAA patients, the CVs for repeated diameter measurements were 2.38% (range 0.87%–4.98%), 2.92% (range 0.72%–5.45%), and 2.17% (range 0.32%–5.27%) for observers 1, 2, and 3, respectively. For volume measurements, the CVs were 4.86% (1.44%–9.61%), 5.42% (2.67%–10.02%), and 3.91% (0.81%–9.44%) for observers 1, 2, and 3, respectively. For calculated PWS, the reproducibility was 3.20% (1.31%–8.24%), 3.78% (0.95%–7.86%), and 3.14% (0.93%–6.99%), respectively. Intraobserver validation for the PWRR index produced CVs of 3.83% (1.43%–8.10%), 4.24% (1.96%–9.86%, and 4.21% (0.78%–8.59%) for observers 1, 2, and 3, respectively. An example of the concordance of PWS distributions for repeated measurements by the 3 observers is shown in Figure 1.

Interobserver Validation

Interobserver reproducibility expressed as the ICC was 0.97 (range 0.95–0.98) for diameter

TABLE 2

Intra- and Interobserver Reproducibility in Diameter, Volume, Peak Wall Stress, and Rupture Risk Estimates for 3 Observers Using Semiautomatic Finite Element Analyses of Infrarenal Aortic Aneurysms

	Observer*	Measurement	CV, %	Variation in CV, %
Maximal diameter, mm	1	60.14±7.24	12.04	0.62
	2	60.80±7.04	11.59	
	3	61.10±7.46	12.21	
Aortic volume, mL	1	189921±69818	36.76	5.64
	2	193891±72342	37.31	
	3	193169±81909	42.40	
Peak wall stress, kPa	1	198.59±38.75	19.51	1.00
	2	202.62±40.28	19.88	
	3	198.91±40.81	20.52	
Rupture risk	1	0.44±0.12	27.65	2.55
	2	0.45±0.12	27.76	
	3	0.43±0.13	30.20	

Measurements are presented as the mean ± standard deviation (SD).
CV: coefficient of variation (SD/mean × 100). The variation of CV% represents the interobserver variability among the 3 observers for all 150 measurements.
* 50 measurements for each observer.

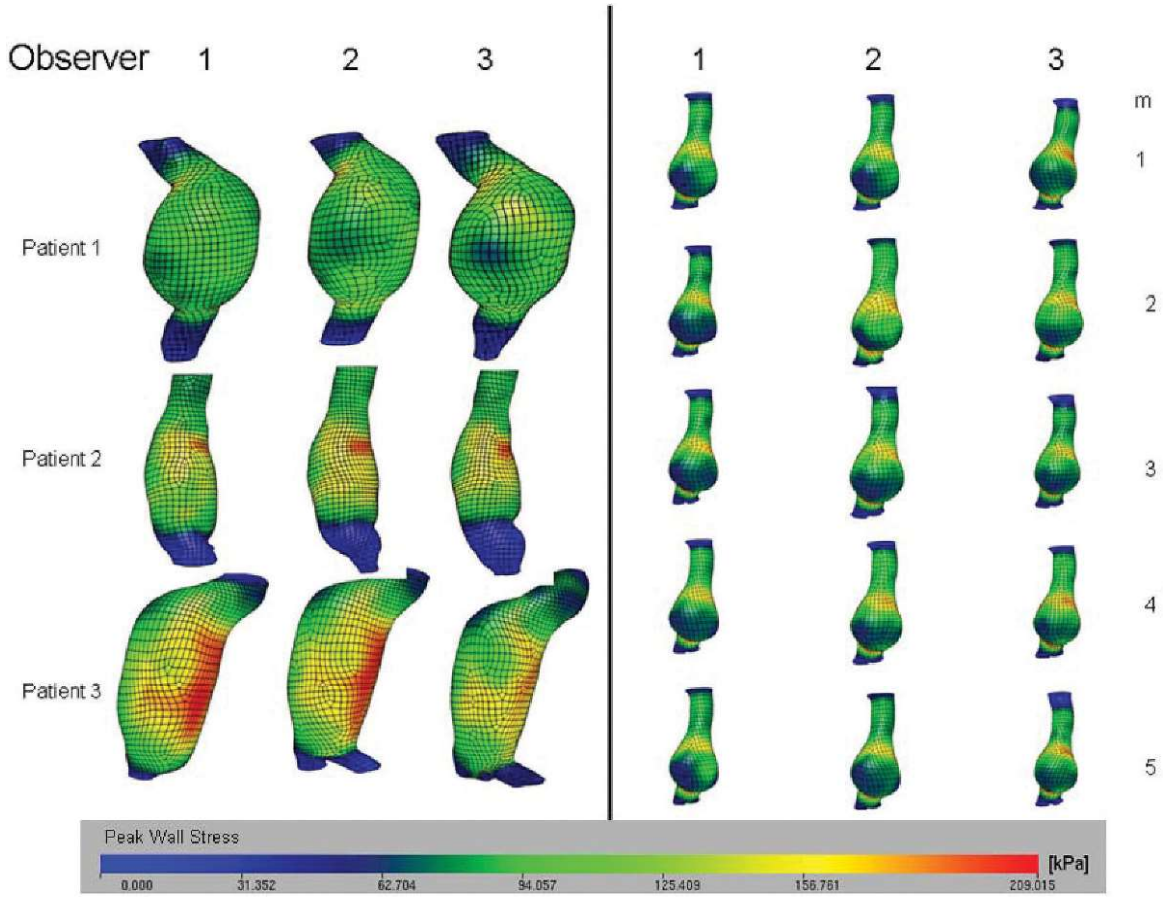

Figure 1 ◆ Distribution of aortic wall stress in 3D FE models. Note the high intraobserver reproducibility on the left in 3 different AAA patients measured by the 3 different observers. Interobserver reproducibility was also high, as shown on the right. Here, the wall stress in the same patient was measured 5 times (m1–5) by each of the 3 observers (m denotes measurement).

estimation and 0.98 (range 0.97–0.99) for volume. Validation of the PWS calculations of the 3 observers showed only minimal deviations, with an ICC of 0.98 (range 0.97–0.99). Furthermore, there was a substantial concordance in the ICC (0.98) for the PWRR (range 0.97–0.99).

Figure 2 shows the Bland-Altman plots for maximum diameter, volume, PWS, and the PWRR, comparing the measurements among the 3 observers. Most values were located within ± 1.96 SDs of the mean differences, which shows a high agreement among the observers. The interobserver reproducibility for diameter measurements was in a range of ± 4 mm in 150 measurements; 95% of the volume measurements showed differences <50 mL among the observers. For all measurements in the AAA dataset, except for the volume measurement, the differences in CVs (Table 2) were $<3\%$. Although the CV for the volume measurement was 5.6%, this implies a variation of only 4 mL among the different observers.

DISCUSSION

The present study shows that anatomy-based centerline measurement of aneurysm diameter and volume and calculations of PWS and the PWRR index can be accomplished with high intra- and interobserver reproducibility in a reasonable time (25–48 minutes) using a semiautomatic vascular analyzer based on FE

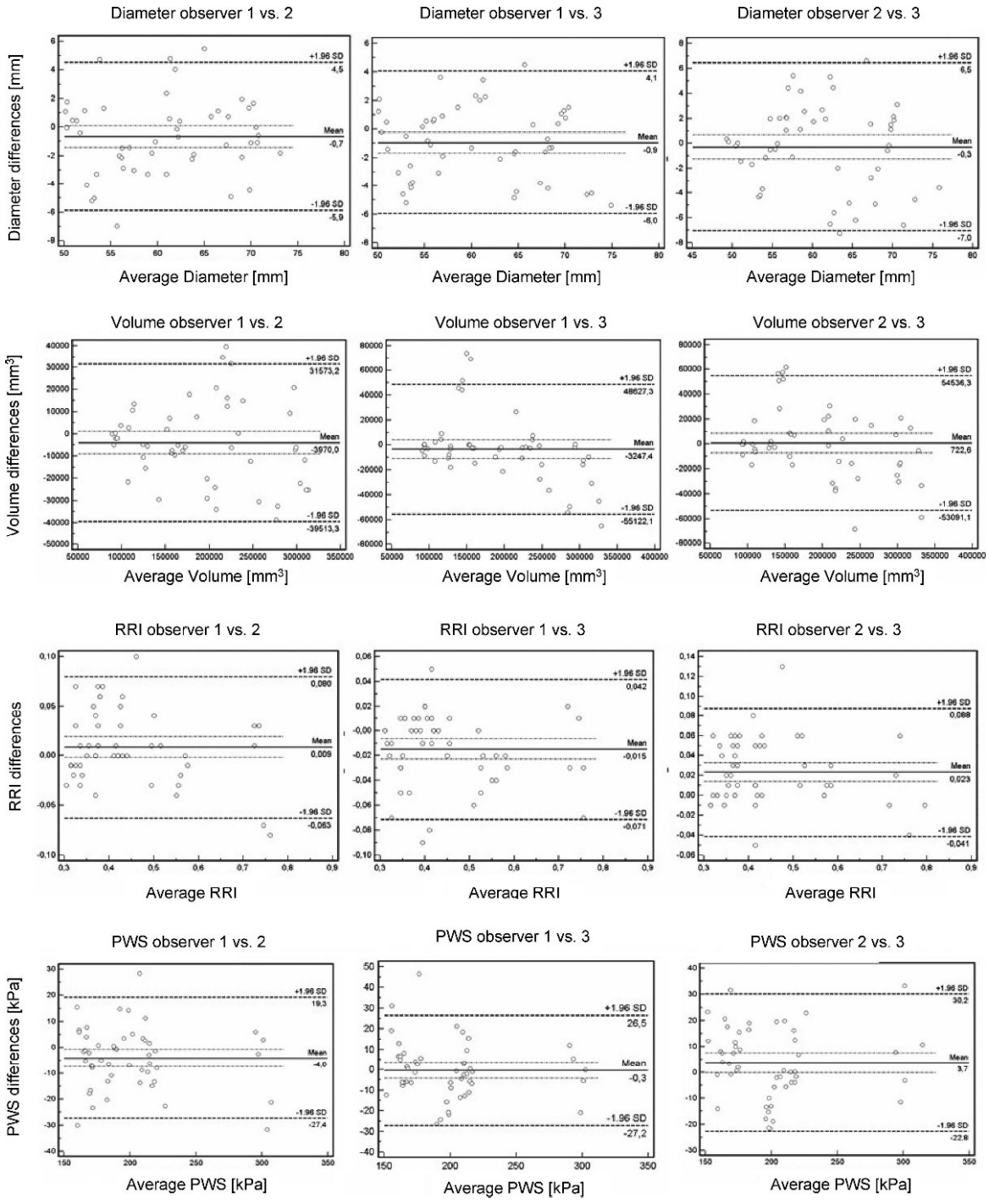

Figure 2 ◆ Bland-Altman plots for diameter, volume, peak wall stress (PWS), and peak wall rupture risk index (RRI) for observers 1 vs. 2, observers 1 vs. 3, and 2 vs. 3. SD: standard deviation; dotted line indicates 1.96×SD.

models of infrarenal nonruptured AAAs. Whereas previous studies dealt with the feasibility of different wall stress analyses using FE models,[3,13–15] we focused this work on the reproducibility of measuring the study parameters using an FE-based vascular analyzer.

Aneurysm Diameter

The law of Laplace suggests a linear relationship between diameter and wall stress (and thus rupture risk). Therefore, most surgeons evaluating AAA patients base their decision to intervene surgically on the aneurysm diameter.[16] However, aneurysm diameters measured on axial ultrasound or CTA scans may be erroneous, especially in an angulated or tortuous aorta.[17] Additionally, measurements from axial CT images show substantial interobserver variability, which can be reduced using postprocessing software with 3D reconstructed images and perpendicular measurements along a centerline.[18] Kauffmann et al.[19] found very high interobserver reproducibility (ICC 0.97) for the maximum aneurysm diameter assessed using this type of postprocessing software. Our study produced similar results (ICC 0.99) using an FE-based vascular analyzer that reconstructs CT data into 3D models along an anatomically-based centerline, not the lumen-based centerline that is used in most of today's image postprocessing software to our knowledge.

Aneurysm Volume

In addition to aneurysm diameter, aneurysm volume can also be extracted from FE models with this analyzer software. Volume measurements might offer a more reliable parameter to quantify aneurysm growth or shrinkage (e.g., during follow-up). Our study showed that infrarenal volumes in normal aortas are ~15 mL, with intra- and interobserver reproducibility between 6% and 12%; thus, volume changes of 5 mL could be detected in surveillance of a healthy cohort. The volumes of the infrarenal aneurysms ranged between 92 and 312 mL, with a coefficient of variation of ~5% for repeated measurements in 1 observer. The interobserver reproducibility was high among the observers as well, so volume changes between 4.5 and 15 mL could be visualized with the FE model in this software. This high intra- and interobserver reproducibility is in line with the currently used CTA-based volume measurements (coefficient of variation $<4\%$).[20]

PWS and PWRR Index Prediction

The law of Laplace is based on cylindrical geometries and is thus not completely applicable to the sometimes complex geometry of an infrarenal AAA. In particular, the law can be applied only to thin-walled structures, i.e., AAAs without thrombus formation. Although a thrombus cannot negate the pressure acting at the wall, its presence can in certain cases significantly reduce the wall stress.[21] Therefore, maximum aneurysm diameter measurements may not be valid as a sole parameter for patient-specific rupture risk prediction, and additional parameters to facilitate a more profound decision toward treatment indication are required. PWS and, slightly better, the PWRR index,[3] could qualify and appear to be superior to diameter measurements alone in differentiating AAA patients who will experience a fatal outcome.[4] In our small cohort, we found no linear correlation between diameter and PWS or the PWRR index. The highest PWS and PWRR index were found in an aneurysm measuring 71 mm in diameter. On the other hand, we found different PWS/PWRR index values in aneurysms with almost the same diameter (Table 3).

Reproducibility of PWS has been described with high accuracy in patients with AAA.[13] Excluding the 1% of nodes containing the highest wall stress (99-percentile stress), Speelman et al.[13] increased the interobserver ICC in their 20-patient study from 0.71 to 0.95. In our study, the 0.98 interobserver ICC indicates high reproducibility without any corrections/exclusions. Although PWS calculations might improve rupture prediction, the actual location of rupture might not always correspond to the region of highest wall stress. Therefore, additional variables known to influence the risk of rupture (e.g., gender, history of smoking) were implemented to improve FE models[15,22] and calculate

TABLE 3
Conventional Diameter Measurements Compared With Diameter Estimates From Finite Element (FE) Analyses of 10 Patients With Infrarenal AAA

Patient	Conventional Diameter on CTA, mm	Diameter From FE Model, mm	Difference, mm	PWS, kPa	PWRR
1	5.5	5.3	−0.2	200	0.38
2	6.0	6.2	+0.2	190	0.40
3	5.6	5.8	+0.2	164	0.35
4	5.4	5.6	+0.2	214	0.50
5	5.0	5.3	+0.3	174	0.38
6	6.7	7.1	+0.4	299	0.74
7	5.1	5.0	−0.1	163	0.32
8	6.3	6.9	+0.6	216	0.56
9	6.5	6.3	−0.2	167	0.34
10	6.8	6.7	−0.1	209	0.43

CTA: computed tomographic angiography, PWS: peak wall stress, PWRR: peak wall rupture risk index.

the PWRR index or rupture potential index (RPI) as evaluated by Gasser et al.,[3] Maier et al.,[22] and Vande Geest et al.[23] For calculation of these risk indices, the structural analysis has to consider (apart from PWS) the intraluminal thrombus, the normal infrarenal aortic diameter, gender, and family history. The results showed an increased risk index in symptomatic or ruptured AAA compared to asymptomatic AAAs, which indicates that these indices might be a step toward a more accurate individual rupture risk prediction score that could greatly improve clinical decision making.[3,22,23]

Intra- and interobserver reproducibility of the PWRR index was in the same range as that found for diameter, volume, and PWS. However, some of the FE models have not included the intraluminal aortic thrombus in their PWS calculations,[5–8] despite the finding that intraluminal aortic thrombus is associated with an increased risk of rupture for AAA in other investigations.[24] The calculation of the PWRR or RPI index in the studies of Gasser et al.[3] and Maier and colleagues[22] included intraluminal thrombus because it impacts AAA biomechanics by influencing the proteolytic degradation of the underlying aneurysm wall and therefore increases the risk of rupture.[25,26] Our study supports the contention that modern FE models should include thrombus tissue in their analysis. Despite these early encouraging results, further validation of PWS and the PWRR index has to be performed before implementing this technology into clinical practice.

Time Requirements

This analysis shows that not only aneurysm diameter but also volume measurements and PWS/PWRR index calculations are reproducible parameters within FE models. The advantage of this model is that all measurement parameters can be estimated using one semiautomatic tool and thus reduce the large amount of time required to segment and analyze FE models (which might be considered one major clinical drawback of this method). In our study, the mean time necessary to perform the analysis in infrarenal AAAs was 39 minutes, which is a decided improvement over manual segmentation models or to FE models requiring many time-consuming manual corrections. Additionally, with ongoing software development and observers surmounting the learning curve, segmentation time can be dramatically reduced, which is a necessity for introduction of such systems into clinical use.

Limitations

Notably, the small number of patients could be a limitation, although ≥200 FE models were constructed and analyzed. FE models are mathematic tools that are used to calculate strength and stress in construction projects or

for simulating crash tests in automotive industry. In these fields, boundary and loading conditions for the materials are much simpler than human aortic tissue. Therefore, validation of FE models, for example, with correlation to histopathological findings, is needed and will be addressed in future studies. More information concerning stress and strength and their interaction with thrombus and calcification has to be considered to improve FE models.

At present, we have not yet introduced into the 3D FE models any patient parameters (e.g., history of smoking or genetic influences) that might influence the risk of AAA rupture. Including these individual parameters, we could use a semiautomatic, time-optimized FE model–based vascular analyzer to assess a risk of rupture for each aneurysm patient and thus improve clinical decision making in the future.

Conclusion

Semiautomatic reconstruction software using FE models can provide anatomy-based centerline diameter and volume measurement and estimates of PWS and the PWRR index in infrarenal aneurysms with high intra- and interobserver reproducibility in a reasonable time range. On the basis of these models, changes in aortic diameter, volume, and PWS over time may be monitored with high precision in the near future, which could lead to a more individualized rupture risk prediction in AAA patients.

Acknowledgment: We are grateful to Caterina Dal Col for editing the manuscript.

REFERENCES

1. Nicholls SC, Gardner JB, Meissner MH, et al. Rupture in small abdominal aortic aneurysms. *J Vasc Surg*. 1998;28:884–888.
2. Vorp DA, Vande Geest JP. Biomechanical determinants of abdominal aortic aneurysm rupture. *Arterioscler Thromb Vasc Biol*. 2005; 25:1558–1566.
3. Gasser TC, Auer M, Labruto F, et al. Biomechanical rupture risk assessment of abdominal aortic aneurysms: model complexity versus predictability of finite element simulations. *Eur J Vasc Endovasc Surg*. 2010;40:176–85.
4. Fillinger MF, Marra SP, Raghavan ML, et al. Prediction of rupture risk in abdominal aortic aneurysm during observation: wall stress versus diameter. *J Vasc Surg*. 2003;37:724–732.
5. Fillinger MF, Raghavan ML, Marra SP, et al. In vivo analysis of mechanical wall stress and abdominal aortic aneurysm rupture risk. *J Vasc Surg*. 2002;36:589–597.
6. Heng MS, Fagan MJ, Collier JW, et al. Peak wall stress measurement in elective and acute abdominal aortic aneurysms. *J Vasc Surg*. 2008;47:17–22.
7. Truijers M, Pol JA, Schultzekool LJ, et al. Wall stress analysis in small asymptomatic, symptomatic and ruptured abdominal aortic aneurysms. *Eur J Vasc Endovasc Surg*. 2007;33: 401–407.
8. Venkatasubramaniam AK, Fagan MJ, Mehta T, et al. A comparative study of aortic wall stress using finite element analysis for ruptured and non-ruptured abdominal aortic aneurysms. *Eur J Vasc Endovasc Surg*. 2004;28:168–176.
9. Riva-Rocci S, Zanchetti A, Mancia G. A new sphygmomanometer. Sphygmomanometric technique. *J Hypertens*. 1996;14:1–12.
10. Auer M, Gasser T. Reconstruction and finite element mesh generation of abdominal aortic aneurysms from computerized tomography angiography data with minimal user interactions. *IEEE Trans Med Imaging*. 2010;29:1022–1028.
11. Bartko JJ. The intraclass correlation coefficient as a measure of reliability. *Psychol Rep*. 1966;19:3–11.
12. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*. 1986;1:307–310.
13. Speelman L, Bosboom EM, Schurink GW, et al. Patient-specific AAA wall stress analysis: 99-percentile versus peak stress. *Eur J Vasc Endovasc Surg*. 2008;36:668–676.
14. Speelman L, Hellenthal FA, Pulinx B, et al. The influence of wall stress on AAA growth and biomarkers. *Eur J Vasc Endovasc Surg*. 2010; 39:410–416.
15. Georgakarakos E, Ioannou CV, Papaharilaou Y, et al. Peak wall stress does not necessarily predict the location of rupture in abdominal aortic aneurysms. *Eur J Vasc Endovasc Surg*. 2009;39:302–304.
16. McGloughlin TM, Doyle BJ. New approaches to abdominal aortic aneurysm rupture risk assessment. Engineering insights with clinical gain. *Arterioscler Thromb Vasc Biol*. 2010;30: 1687–1694.
17. Broeders IA, Blankensteijn JD, Olree M, et al. Preoperative sizing of grafts for transfemoral endovascular aneurysm management: a pro-

spective comparative study of spiral CT angiography, arteriography, and conventional CT imaging. *J Endovasc Surg*. 1997;4:252–261.
18. Cayne NS, Veith FJ, Lipsitz EC, et al. Variability of maximal aortic aneurysm diameter measurements on CT scan: significance and methods to minimize. *J Vasc Surg*. 2004;39:811–815.
19. Kauffmann C, Tang A, Dugas A, et al. Clinical validation of a software for quantitative follow-up of abdominal aortic aneurysm maximal diameter and growth by CT angiography. *Eur J Radiol*. 2011;77:502–508.
20. Parr A, Jayaratne C, Buttner P, et al. Comparison of volume and diameter measurement in assessing small abdominal aortic aneurysm expansion examined using computed tomographic angiography. *Eur J Radiol*. 2010; January 8 [Epub ahead of print].
21. Thubrikar MJ, Robicsek F, Labrosse M, et al. Effect of thrombus on abdominal aortic aneurysm wall dilation and stress. *J Cardiovasc Surg (Torino)*. 2003;44:67–77.
22. Maier A, Gee MW, Reeps C, et al. A comparison of diameter, wall stress, and rupture potential index for abdominal aortic aneurysm rupture risk prediction. *Ann Biomed Eng*. 2010;38:3124–3134.
23. Vande Geest JP, Di Martino ES, Bohra A, et al. A biomechanics-based rupture potential index for abdominal aortic aneurysm risk assessment: demonstrative application. *Ann N Y Acad Sci*. 2006;1085:11–21.
24. Stenbaek J, Kalin B, Swedenborg J. Growth of thrombus may be a better predictor of rupture than diameter in patients with abdominal aortic aneurysms. *Eur J Vasc Endovasc Surg*. 2000;20:466–469.
25. Kazi M, Thyberg J, Religa P, et al. Influence of intraluminal thrombus on structural and cellular composition of abdominal aortic aneurysm wall. *J Vasc Surg*. 2003;38:1283–1292.
26. Vorp DA, Lee PC, Wang DH, et al. Association of intraluminal thrombus in abdominal aortic aneurysm with local hypoxia and wall weakening. *J Vasc Surg*. 2001;34:291–299.