Impact of aortoiliac tortuosity on endovascular repair of abdominal aortic aneurysms: Evaluation of 3D computer-based assessment

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Objective: The purpose of this study was to examine the effect of aortoiliac tortuosity, as assessed by observers and 3-dimensional (3D) computer-based methods, on the conduct and outcome of endovascular repair of abdominal aortic aneurysms.

Methods: Infrarenal aortoiliac tortuosity was measured in 75 patients (mean follow-up, 14.8 ± 10.4 months) who underwent endovascular repair of abdominal aortic aneurysms by using the following four methods: (1) grading by 2 experienced observers; (2) tortuosity index measured as the inverse radius of curvature (cm⁻¹) at 1-mm intervals along the median luminal centerline (MLC) on 3D reconstructions of computed tomography (CT) angiograms and was calculated as the sum of values greater than 0.3 cm⁻¹; (3) MLC–straight line length ratio from renal to hypogastric arteries; (4) manual measurement of angles at points of angulation on anteroposterior and lateral projections of 3D CT reconstructions. In evaluating association between these measures, correlation between human observers was accepted as the gold standard.

Results: For rating of overall aortoiliac tortuosity, interobserver correlation (r = 0.67) was comparable with correlation of observers with tortuosity index (r = 0.67 and 0.56), whereas correlations of each observer with MLC–straight line ratio (r = 0.50 and 0.56) and cumulative angulation (r = 0.44 and 0.44) were significant but weaker. For determining the relative tortuosity of right and left aortoiliac access, agreement between observers and tortuosity index (54% and 58%; P < .05; κ, 0.33 and 0.38) was not as good as between observers (68%; P < .001; κ, 0.53). This difference was primarily related to evaluation of the aorta, where interobserver correlation (r = 0.71) was better than that between each observer and tortuosity index (r = 0.47 and 0.55), whereas correlations in the iliac arteries were comparable (r = 0.64 and 0.67) (all coefficients P < .01). Increased tortuosity was associated with a more complex endovascular repair, as reflected by longer fluoroscopy time (P = .05), use of more contrast material (P = .03), use of extender modules (P = .04), and more frequent use of arterial reconstruction (P = .01), but was not associated with a higher overall complication rate. Increased tortuosity, when it occurred in the aortic neck, was associated with predischarge endoleak (P = .03) but not with late endoleak, intervention, or aneurysm-related adverse events.

Conclusion: Aortoiliac tortuosity is associated with increased complexity of endovascular aneurysm repair and with predischarge endoleak but does not appear to affect intermediate-term results. Computer-based 3D measurement of aortoiliac tortuosity is feasible and clinically meaningful. Its ultimate role in relation to human assessment must be further defined in future studies. (J Vasc Surg 2001;34:594-9.)

Successful endovascular repair of abdominal aortic aneurysms depends on adequate iliofemoral access and accurate delivery of all components of the stent graft, both of which are clearly influenced by aortic and iliac tortuosity, which can pose a challenge to endovascular aneurysm repair (Fig 1). Tortuosity may also affect the stability of endograft fixation, and it has been implicated as a cause of late complications and endograft failure through progressive distortion and limb retraction. The concept of tortuosity is intuitive and easily comprehensible but is most commonly used in a qualitative and subjective manner. Quantitation of tortuosity is quite complex; there is no consensus on the best method of measurement, and it is not commonly done. Computerized measurement of vascular tortuosity has been performed in the coronary and retinal circulations and for evaluation of atherogenesis in the femoral artery. In the context of endovascular aneurysm repair, methods to standardize measurement of aortoiliac tortuosity and, particularly, the application of computer-aided quantification, could enhance planning, communication, follow-up, and the development of standards and guidelines. Indeed, in a recent analysis of a smaller group of initial patients after endovascular aneurysm repair, some of whom are included in this report, computer-based assessment was performed and demonstrated an increased rate of asymptomatic iliofemoral dissections in more tortuous arteries.

In this article, we have evaluated methods for measurement of aortoiliac tortuosity, conducted a comparison between them, and assessed the impact of aortoiliac tortu-
osity on endovascular aneurysm repair and its eventual outcome.

PATIENTS AND METHODS

Evaluation of aortoiliac tortuosity was performed retrospectively on 75 patients who underwent endovascular aneurysm repair with the Medtronic AneuRx (Santa Rosa, Calif) stent graft at Stanford University hospital during a period of 3 years. All other information, including demographic data, comorbidity, aneurysm morphology, procedure, and follow-up, were acquired prospectively. Mean follow-up in these patients was 14.8 ± 10.4 months (median, 12.0 months).

The standard endovascular technique included placement of a superstiff guidewire in all patients and sheaths (22 F for the primary module and 16 F for the secondary module). The primary module was inserted preferentially through the less tortuous side. The principal surgical maneuver to handle tortuosity was mobilization of the distal external iliac artery so that insertion could be facil-

![Fig 1. Examples of increased tortuosity. A, The most tortuous common iliac artery with a “hair pin” configuration evaluated in a patient who underwent endovascular aneurysm repair. B, A transverse proximal aortic neck in a 92-year-old woman, which could not be cannulated. The patient underwent an uneventful open aneurysm repair. C, Tortuous iliac arteries, typical of advanced age, in an 86-year-old patient who underwent an uneventful endovascular aneurysm repair. D, An aneurysm considered too tortuous for endovascular repair. Notice the left common iliac artery with an acute angulation just below the aortic bifurcation.](image-url)
iterated by counter-traction and straightening of the external iliac artery.

Tortuosity of the aorta and iliac arteries was graded (1, none [straight segment]; 2, mild; 3, moderate; 4, severe; 5, extreme) on anteroposterior and lateral projections of 3D renderings of spiral computed tomography (CT) angiograms by two vascular surgeons experienced in evaluation of such images (YGW, WAL). Both surgeons were involved in the care of some patients, but during evaluation of the images they were unaware of the identity of the patients, and a conscious effort was made to conduct an unbiased assessment. Evaluation was conducted independently by both observers and included the aorta and both common and external iliac arteries separately, in addition to overall assessment and comparison of sides. The infrarenal neck was specifically evaluated and graded.

Computer-based measurement of infrarenal aortoiliac tortuosity was performed in one of two ways, both relying on construction of the median luminal centerline (MLC). After extraction of the contrast-enhanced flow channel from helical CT angiographic image data, and manual selection of the limits of calculation, the MLC was computed and orthogonal cross-sections were created at 1-mm intervals. The path was smoothed to provide closed-form expressions of derivatives along the path to allow for calculation of curvature at discrete intervals along the MLC.

One computer-based method, tortuosity index, entailed measurement of point tortuosity, defined as the inverse of the radius of curvature (cm\(^{-1}\)) at 1-mm intervals along the MLC from renal artery origin to the femoral arteries. Based on a preliminary evaluation by a panel of vascular surgeons and radiologists, a value of less than 0.3 cm\(^{-1}\) (corresponding to a radius of 3.3 cm) was considered inconsequential. Tortuosity index was defined as the sum of values >0.3 cm\(^{-1}\) along the segment of interest. In addition to tortuosity index, the maximal value of tortuosity was noted for each segment. The computer software was developed at Stanford University and has been described previously.\(^9\)

The second computer-based method, MLC–straight line ratio, was intended to produce an overall assessment of aortoiliac tortuosity. This was defined as the ratio of the length of the MLC to the straight line from the renal arteries to the origin of the hypogastric arteries and gave a measure of overall “redundancy” (Fig 2). The straight-line distance was calculated as the hypotenuse of the right triangle made from the craniocaudal distance between renal and hypogastric arteries and half the distance between hypogastric artery origins.

The fourth method for quantifying tortuosity, cumulative angulation, was defined as the sum of all angles (deviation from the straight path in degrees) at points of angulation, as measured manually from anteroposterior and lateral views of 3D projections from the renal to the hypogastric arteries. The recorded angle for each site was the higher value of either anteroposterior or lateral view.

All of these methods are attempts at quantifying aortoiliac tortuosity, and none of them measure the actual path taken by the endograft. The Pearson correlation coefficients between values of these tortuosity indices along the aorta and iliac arteries were examined. Grading by human observers was compared among observers and with tortuosity index for determination of relative tortuosity of right and left aortoiliac access. In the absence of established standards, correlation between human observers was used as the gold standard, realizing that in reality, tortuosity index and other computer-based measures may well be superior to human assessment.

All indices of aortoiliac tortuosity were evaluated for association with procedure-related variables. These included length of operation, blood loss, fluoroscopy time, amount of contrast material used, arterial reconstruction (more extensive than local entry site endarterectomy or patch angioplasty), use of stent graft extender modules, and postoperative complications. Tortuosity measurements for this purpose were evaluated for the aorta and the iliac artery on the side of insertion of the primary bifurcation module, which required the larger

Fig 2. Maximum-intensity projection of an infrarenal aortic aneurysm and common iliac arteries. The dashed line represents the MLC. MLC–straight line ratio consisted of the length of the MLC from A to B divided by the length of the straight line between these two points. A potential source of overestimation of tortuosity within the aneurysm is shown. Because of its dependence on aneurysm configuration, the MLC may follow an angulated course (arrows) that is unrelated to the course hardware traversing the aneurysm. This type of angulation is related to the construction of the MLC and is more accentuated in eccentric and saccular flow patterns within the aneurysm.
Table I. Correlation between measures of aortoiliac tortuosity*

<table>
<thead>
<tr>
<th>Measure</th>
<th>Sum of angulation (degrees)</th>
<th>MLC-straight line ratio</th>
<th>Tortuosity index</th>
<th>Observer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observer 1</td>
<td>0.44 (0.41)</td>
<td>0.50 (0.48)</td>
<td>.59 (0.56)</td>
<td>0.67 (0.65)</td>
</tr>
<tr>
<td>Observer 2</td>
<td>0.43 (0.41)</td>
<td>0.56 (0.59)</td>
<td>.71 (0.67)</td>
<td>0.67 (0.65)</td>
</tr>
<tr>
<td>Tortuosity index</td>
<td>0.24</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall MLC–based tortuosity</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Pearson correlation coefficients are shown, and Spearman ρ statistics for interval data are included in parentheses. All coefficients were significant at P < .05.

Table II. Association between determinations of relative tortuosity of right and left aortoiliac access between two observers and tortuosity index

<table>
<thead>
<tr>
<th>Statistical test</th>
<th>Obs 1 and Obs 2</th>
<th>Obs 1 and TI</th>
<th>Obs 2 and TI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agreement on relative tortuosity of right and left sides, χ²*</td>
<td>Agree, 68%; discrep, 6%</td>
<td>Agree, 54%; discrep, 13%</td>
<td>Agree, 58%; discrep, 10%</td>
</tr>
<tr>
<td>Agreement on relative tortuosity of right and left sides, κ (P &lt; .01)</td>
<td>0.53</td>
<td>0.33</td>
<td>0.38</td>
</tr>
<tr>
<td>Pearson correlation coefficient of aortic tortuosity (P &lt; .01)</td>
<td>0.71</td>
<td>0.47</td>
<td>0.55</td>
</tr>
<tr>
<td>Pearson correlation coefficient of iliac tortuosity (P &lt; .01)</td>
<td>0.67</td>
<td>0.64</td>
<td>0.67</td>
</tr>
</tbody>
</table>

*Possible answers were right, left, and equal. Tortuosity index was deemed equal if the difference between sides was less than an arbitrarily set value of 0.5, which included 34% of cases, similar to the breakdown in observer grading. Agreement was defined as percentage of identical answers. Discrepancy is defined as percentage of contradictory left/right answers, whereas disagreement right/equal or left/equal was not counted. Significance of association is given by the χ² value.

Results

Ratings of overall aortoiliac tortuosity by all 4 methods—observers, tortuosity index, MLC–straight line ratio, and cumulative angulation—correlated significantly. Correlation between observers was comparable with correlation between each observer and tortuosity index, whereas correlations with MLC–straight line ratio and cumulative angulation were weaker (Table I).

For determination of relative tortuosity of right and left aortoiliac access, interobserver agreement was better than agreement between each observer and tortuosity index (Table II). In the iliac arteries, correlations between observers and between each observer and tortuosity index were comparable, whereas in the aorta, correlation between the human observers was better (Table II, Fig 2).

It therefore appears that the lower rate of agreement between observers and tortuosity index was primarily related to differences in assessment of the aneurysmal aortic segment. Comparison with maximal values of tortuosity rather than cumulative values yielded similar results.

Four variables related to procedural complexity of endovascular aneurysm repair were associated with indices of tortuosity. These were fluoroscopy time (24 ± 17 min), quantity of contrast material (110 ± 51 ml), use of stent graft extender modules (n = 36), and arterial reconstruction (n = 14). The use of extender modules was not associated with longer arteries. Observer grading correlated with all four variables, whereas MLC–straight line ratio, tortuosity index, and cumulative angulation correlated with 3 variables, 2 variables, and 1 variable respectively (Table III). Tortuosity index correlated with renal-hypogastric distance (P < .05) and with the use of the longer endograft (P < .05). None of the indices of tortuosity was associated with blood loss, duration of operation, or overall complication rate.

Regarding evaluation of outcome, none of the indices were associated with predischarge endoleak, endoleak at 1 month, persistent or late endoleak, change in aneurysm diameter, need for reintervention, or death. No aneurysm in this series ruptured and none underwent surgical conversion. Grading of tortuosity of the infrarenal aneurysm neck by both observers and infrarenal angulation was significantly associated with predischarge endoleak (P < .05). This included endoleaks of all kinds. Predischarge endoleaks sealed spontaneously in 40% of patients, and only those that persisted beyond 1 month were investigated further. Tortuosity of the neck was not associated with later endoleak, complications, or reinterventions, which were undertaken in 13% of patients.
Arterial tortuosity is known to increase with age (Fig 1, A). Indeed, tortuosity index ($r = 0.38$, $P = .004$), observer grading ($r = 0.26$; $P < .05$), and cumulative angulation ($r = 0.26$; $P < .05$) were found to be associated with age (Fig 3). This was not related to aneurysm size, which did not correlate with tortuosity or with age. Tortuosity did not differ between men and women.

**DISCUSSION**

Aortoiliac tortuosity is an important factor in the selection, planning, conduct, and outcome of endovascular aortic aneurysm repair. Excessive tortuosity may cause difficulty in gaining access to the aneurysm and in the deployment of the stent graft and may result in unstable fixation. In a previous study, we have found that excessive tortuosity was considered the primary reason for disqualifying patients with aneurysms for endovascular repair in 10% to 15% of cases (Fig 1, D). Some of these issues are clearly device-specific. Access is primarily related to the flexibility, diameter, and shape of the delivery system; deployment is related to the modularity of the system; and the mechanism and sequence of deployment and fixation are related to the design of the stent graft. We have used the AneurRx stent graft for all patients included in this study, and the analyses here are pertinent for this device. However, some issues are more general and will probably prove relevant to the use of other stent graft systems as well.

In spite of its central importance, clinically validated methods to quantify tortuosity are unavailable, and evaluation is limited to crude, intuitive assessment. In this study, we evaluated the impact of tortuosity on endovascular abdominal aneurysm repair, with the intent of exam-
ining ways of quantifying tortuosity in a clinically meaningful manner. Theoretically, computer-based 3D assessment of tortuosity is superior to human assessment. It is completely independent of projectional views and is capable of integrating multiple 3D features, including segmental length and local diameter. Even so, at this time, before validation of these methods, we used the correlation between grading by human observers as the gold standard.

All indices of tortuosity evaluated here intercorrelated. Tortuosity index was closest to observer grading, was associated with indicators of complexity of the endovascular procedure and with age, and appears to be a promising index. Its assessment of the aneurysmal aorta was not as good as that of the iliac arteries, and this is probably related to the construction of the MLC. In a narrow artery, the course of the MLC may be a good approximation of the course of the hardware traversing the artery. However, in the aneurysmal aorta, the human observer can intuitively foresee such a course, while the MLC may chart an improbable or unrealistic course (Fig. 2). The great reliance of the MLC–straight line ratio on the aortic wall, or alternatively, defining different segmental lines for the aorta and for the iliac artery.

Cumulative angulation, or the sum of angles measured on projections of the aortoiliac segment, is clearly a simplistic, two-dimensional method to quantify tortuosity with great reliance on projectional views. It was included here for the sake of completeness because it has been used occasionally in reports, particularly to describe the infrarenal neck. Although it is a continuous measure of tortuosity, which may require fulcrum action at the entry site, its association with observer assessment and with procedure variables was lowest and it does not appear to offer an advantage over grading by observers.

Excessive tortuosity as reflected by various indices makes endovascular repair more difficult, but in this series, it did not affect overall complication rate. In a previous study with a smaller group of patients, some of whom are included here, tortuosity was linked with asymptomatic arterial dissection that was identified on follow-up CT angiograms. This was not assessed here. In this study, tortuosity did not affect intermediate-term results, although Umscheid and Stelter have found alterations in stent graft configuration that, they felt, were secondary to tortuosity. Clearly, such findings are related to the stent graft system, patient selection criteria, and the length of follow-up.

Arterial tortuosity is known to increase with age, and indeed higher indices of tortuosity were associated with advanced age. This association may partly explain the higher likelihood of arterial reconstruction and early endoleak in the elderly, although other factors may play a role. Interestingly, our findings indicate that increased tortuosity, which may require fulcrum action at the entry site, is more commonly associated with the need to reconstruct an arterial segment.

In conclusion, aortoiliac tortuosity is associated with increased complexity of endovascular aneurysm repair and with predischARGE endoleak but does not appear to affect early or intermediate-term results. Computer-based 3D measurement of aortoiliac tortuosity is feasible and clinically meaningful but is not entirely comparable with assessment by human observers. Future refinements are expected to increase its utility and may eventually realize its theoretical superiority.

REFERENCES


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