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Abbreviations:

AAA = abdominal aortic aneurysm
IUW = intravascular US withdrawal
MCL = median centerline length
MLC = median luminal centerline
SP = shortest path

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Prediction of Aortoiliac Stent-Graft Length: Comparison of Measurement Methods¹

PURPOSE: To determine the accuracy of helical computed tomography (CT), projectional angiography derived from CT angiography, and intravascular ultrasonographic withdrawal (IUW) length measurements for predicting appropriate aortoiliac stent-graft length.

MATERIALS AND METHODS: Helical CT data from 33 patients were analyzed before and after endovascular repair of abdominal aortic aneurysm (Aneurix graft, $n = 31$; Excluder graft, $n = 2$). The aortoiliac length of the median luminal centerline (MLC) and the shortest path (SP) that remained at least one common iliac arterial radius away from the vessel wall were calculated. Conventional angiographic measurements were simulated from CT data as the length of the three-dimensional MLC projected onto four standard viewing planes. These predeployment lengths and IUW length, available in 24 patients, were compared with the aortoiliac arterial length after stent-graft deployment.

RESULTS: The mean error values of SP, MLC, the maximum projected MLC, and IUW were $-2.1 \text{ mm} \pm 4.6 \text{ (SD)}$ ($P = .013$), $9.8 \text{ mm} \pm 6.8$ ($P < .001$), $-5.2 \text{ mm} \pm 7.8$ ($P < .001$), and $-14.1 \text{ mm} \pm 9.3$ ($P < .001$), respectively. The preprocedural prediction of the postprocedural aortoiliac length with the SP was significantly more accurate than that with the MLC ($P < .001$), maximum projected MLC ($P < .001$), and IUW ($P < .001$).

CONCLUSION: The shortest aortoiliac path length maintaining at least one radius distance from the vessel wall most accurately enabled stent-graft length prediction for 31 AneuRx and two Excluder stent-grafts.

The current standard treatment for abdominal aortic aneurysm (AAA) in patients without substantial comorbid disease, with preclusion of laparotomy, is elective open surgical repair, which has a low overall risk (1.4%–6.5% mortality rate) (1). However, the risk of perioperative death from surgical AAA repair is considerably higher (5.7%–31.0%) in patients with a comorbid medical condition such as severe cardiovascular, pulmonary, or renal disease (1–3). To reduce the surgical risk in patients with comorbid medical conditions, less invasive repair methods have been considered. Treatment of AAA with transfemoral intraarterial deployment of an endovascular stent-graft is becoming a valuable alternative to surgical repair (4–6).

The planning of endovascular repair of AAA puts greater requirements on preoperative imaging because it must provide accurate information on the morphologic structure and quantitative dimensions of the arterial segments involved. Selection of the appropriate stent-graft diameter and length is a key factor in minimizing the most common complications after endovascular repair of AAA: endoleak, branch occlusion, and, rarely, graft thrombosis. Excessively long stent-grafts with an unsupported body may kink or fold, whereas completely supported stent-grafts may cover the orifices of major side branches. If the stent-graft is too short, there is a risk of endoleak or, in rare cases, deployment into the aneurysmal sac (6).

Two-dimensional measurements of computed tomographic (CT) data on the basis of

transverse and craniocaudal dimensions have a potential for substantial measurement error in three-dimensional structures (7,8). Because conventional arteriography is a projectional technique, overlap and parallax limit it for determining appropriate stent-graft length (8,9). Intravascular ultrasonography (US) can provide useful information on aortic wall characteristics and facilitate evaluation of atheromatous and calcified iliac arterial plaques (10,11). However, aortic length measurements based on intravascular US catheter withdrawal may not enable accurate prediction of the length required for an endovascular stent-graft (10). Quantitative volumetric analysis of helical CT scans has been proposed as a more accurate method for planning endovascular repair of AAA (8,12).

The purpose of this investigation was to determine the accuracy of helical CT, projectional angiography derived from CT angiography, and intravascular US withdrawal (IUW) length measurements for predicting appropriate aortoiliac stent-graft length. This was accomplished by (a) developing a hypothesis of the course that aortoiliac arterial stent-grafts tend to follow within an aneurysmal lumen, (b) translating our hypothesis into a predictive measurement of aortic luminal length, and (c) testing our hypothesis by comparing the new measurement method against currently used methods for predicting aortic stent-graft length before deployment.

MATERIALS AND METHODS

Determination of Stent-Graft Course

Helical CT data obtained before and 2 days after deployment of an aortoiliac stent-graft for the treatment of infrarenal AAA were analyzed in 10 consecutive patients. The mean age of the 10 patients (eight men and two women) was 71 years (age range, 63–81 years), and the mean aneurysmal diameter was 58 mm (range, 48–79 mm). All aneurysmal diameters were preoperatively measured from double-oblique helical CT reformations obtained perpendicular to the wall of the aorta at its point of maximal dilation. Three stent-graft types were represented in this group: four aortobiliac stent-grafts (AneuRx; Medtronic, Santa Rosa, Calif), four polyester-covered modified Z-stents (made at Stanford University) in an aortouniiliac configuration, and two tube stent-grafts (EVT, Menlo Park, Calif). For bifurcated stent-grafts, we assessed the primary stent-graft limb only, which corresponded to the component

of the two-component bifurcated system that contains the device bifurcation and receives the secondarily placed contralateral iliac arterial limb.

To determine the deviation in the flow lumen that results after stent-graft deployment, we assumed that the outer wall of the aorta does not change within 2 days after stent-graft deployment. We therefore devised the following method for referencing the center of the flow lumen relative to the outer wall of the aorta on pre- and postdeployment CT scans and for subsequently measuring the displacement of the central axis of the flow lumen (Fig 1).

Ellipses were fit to the outer aortic wall and outer border of the patent lumen of the aortic aneurysm at every centimeter along its length. The center of each ellipse pair thus indicated the center of the aorta and the aortic lumen on each of the measured transverse sections. The ellipses were fit by hand (G.D.R.) by using an ellipse-drawing tool at a CT workstation (Advantage Windows; GE Medical Systems, Milwaukee, Wis) that allowed interactive control of the angle and length of the major and minor axes of the ellipse. A line segment was subsequently traced that joined the centers of each ellipse pair on pre- and postdeployment scans. The transverse displacement (D) of the luminal center between pre- and postdeployment scans relative to the outer aortic wall was thus defined by the lengths ($L1$ = before deployment, $L2$ = after deployment) and angles relative to the CT table ($\theta1$ = before deployment, $\theta2$ = after deployment) and calculated trigonometrically as

$$D = \sqrt{[L1 \sin(\theta2 - \theta1)]^2 + [L2 - L1 \cos(\theta2 - \theta1)]^2}.$$

The maximum displacement of the postdeployment flow luminal center relative to the predeployment flow luminal center was used as an index of overall flow channel displacement for each patient.

The average maximum displacement of the flow lumen after stent-graft deployment was $8.2 \text{ mm} \pm 3.8 \text{ (SD)}$ (range, 4.8–14.1 mm), indicating that the stent-graft did not follow the MLC. Visual inspection of the luminal displacement suggested that the stent-graft tended to follow as straight a course as possible, thus deviating the flow lumen toward the lesser or inner curve of the aorta.

Patient Population

Thirty-three patients (30 men and three women; mean age, 67 years; age range,

45–87 years) with infrarenal AAA underwent helical CT before and after endovascular stent-graft deployment. Only patients without postdeployment endoleaks or other stent-graft-related complications were included. The mean intervals between pre- and postdeployment helical CT relative to stent-graft deployment were $28 \text{ days} \pm 15$ and $4 \text{ days} \pm 2$, respectively. All imaging was performed as part of routine clinical care. A fusiform aneurysm was present in 31 patients; a saccular aneurysm, in two patients. All accessory renal arteries arose above the aneurysmal sac and were thus spared at stent-graft deployment.

Two types of endovascular stent-graft were used: An AneuRx device was deployed in 31 patients, and an Excluder stent-graft (Gore, Flagstaff, Ariz) was deployed in two patients. A bifurcated graft was used in 32 patients; a tube graft, in one patient. All devices were composed of a self-expanding nitinol skeleton covered with woven polyester graft material.

The primary limb of the AneuRx stent-grafts and the entirety of the Excluder stent-grafts were inserted by way of surgical femoral arteriotomy over an extra-stiff guide wire within a 22-F introducer sheath for the AneuRx device and within an 18-F sheath for the Excluder device. For bifurcated grafts, the contralateral femoral artery was punctured after primary limb deployment, and the secondary limb was inserted through a 16-F introducer sheath for the AneuRx graft and through a 12-F sheath for the Excluder stent-graft.

Helical CT data were obtained by using one of two CT scanners (HiSpeed Advantage, GE Medical Systems; or Somatom Plus 4, Siemens, Iselin, NJ). CT angiography was performed to image from the celiac origin to the bifurcation of the femoral arteries in a single acquisition. A detailed description of this protocol was published previously (13).

Measurement of Aortoiliac Luminal Length

To identify the median luminal centerline (MLC) of the aortoiliac arterial lumen, pre- and postdeployment image data were transferred to a computer workstation (O2; Silicon Graphics, Mountain View, Calif) with an R5000 processor chip (180-MHz IP 32 processor) with 256 MB of RAM. Linear interpolation was performed to create isotropic voxels. The contrast material-enhanced flow channel was extracted with three-dimensional region growing (14,15). Two authors (K.P.

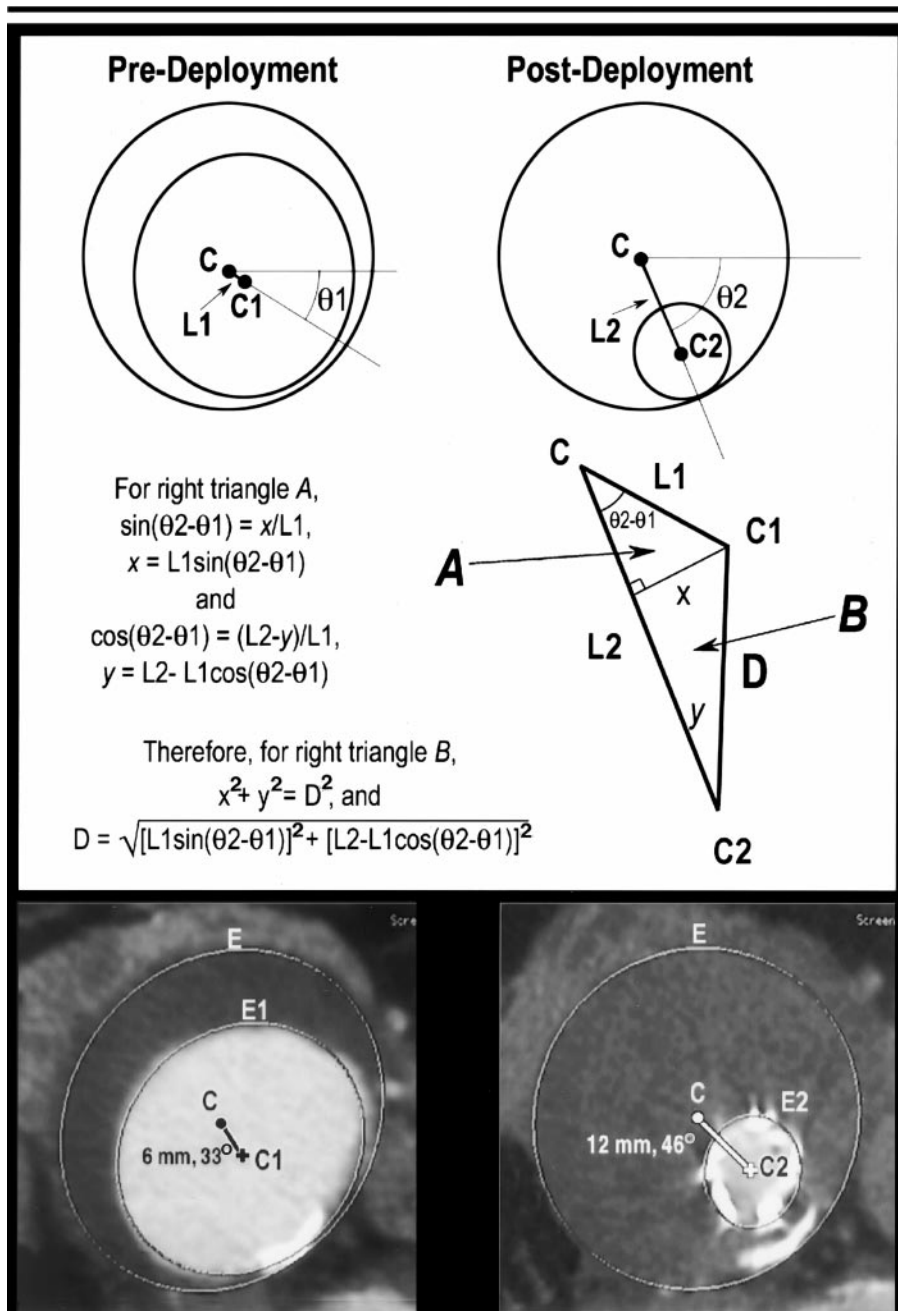


Figure 1. Top: Schematic representation of a transverse section of the pre- and postdeployment aorta. *C* = center of outer aortic wall, *C1* = center of predeployment flow lumen, *C2* = center of postdeployment flow lumen, *L1* = distance between *C* and *C1*, *L2* = distance between *C* and *C2*, θ_1 = angle of *L1* relative to CT table, and θ_2 = angle of *L2* relative to CT table. The displacement (*D*) of the flow lumen after stent-graft deployment was calculated as shown. Transverse CT sections obtained at the same level within an aortic aneurysm before (bottom left) and after (bottom right) stent-graft repair. An ellipse (*E*) with center (*C*) conforms to the outer aortic wall on both images. An ellipse (*E1*) with center *C1* conforms to the wall of the flow lumen before deployment, and an ellipse (*E2*) with center *C2* conforms to the wall of the flow lumen after deployment. In this example, *L1* = 6 mm, *L2* = 12 mm, and $\theta_2 - \theta_1 = 13^\circ$, resulting in 6.3-mm flow lumen displacement after endovascular repair.

and M.T.) manually selected three points within the supraceliac aorta and bilateral femoral arteries, respectively. The median centerline of the contrast-enhanced lumen was computed between these points by

means of a median axis transform, which used a morphologic operation that thinned the segmented flow lumen from the outside in. What remained after this "erosion" was a set of connected

points that defined the MLC through the aorta and iliac arteries (Fig 2) (12). Subsequently, orthonormal cross-sections of the aortoiliac flow lumen were automatically created at every millimeter along the path, as described in reference 12.

Visualization was by means of an interactive graph of the result that allowed the user to drag a cursor to any point along the graph. The corresponding point was shown in a three-dimensional model containing a point-cloud representation of the surface of the segmented volume, the path, the current position along the path, and the orthonormal cross-section through the current position. The origin of the most inferior renal artery was indicated with a small localized peak, and a distinct reduction in mean diameter indicated the origin of the external iliac artery on the graph. Two mouse clicks were used to select these positions on the graph. The automatically displayed corresponding orthonormal sections at each location were viewed to confirm the renal arterial and external iliac arterial origins, and the median centerline lengths (MCLs) of the infrarenal aorta and common iliac artery were thus established as the distance between the two points on the graph. This graphic confirmation of MLC origin and terminus identification allowed measurement subjectivity to be minimized (Fig 3). The mean luminal diameter orthonormal to the median centerline and the curvature of the centerline were determined at every millimeter along the path, as described in reference 12, to assess the relationship of luminal diameter and curvature with the accuracy of length measurements.

On the basis of our observation that the primary limb of stent-grafts tends to follow the shortest path (SP) through the aortoiliac lumen, we developed a computer algorithm to automatically calculate this path and its length as a means of accurately predicting the appropriate length of the primary stent-graft component by using predeployment anatomic structures (Fig 2). The SP was calculated automatically by using an algorithm that creates a path simulating a taut string through the aortic lumen, constrained to lie a distance, *R*, from the vessel wall. The only user interactions were selection of the most inferior renal arterial origin and common iliac arterial bifurcation with two mouse clicks, as described for MLC measurement, and selection of the radius of the stent-graft to be deployed. The purpose of the latter constraint was to account for the fact that the center of the stent-graft lumen will lie not against the

edge of the aortic flow lumen but rather a distance, R , equal to the radius of the stent-graft, so that the wall of the stent-graft may rest against the inner curve of the aortic lumen.

On the basis of the assumption that the stent-graft diameter would approximate the diameter of the anticipated distal fixation site, we specifically designated the R value to be equal to the radius of the anticipated distal fixation site of the primary stent-graft component. This corresponded to the distal common iliac artery or distal abdominal aorta just before its bifurcation in patients receiving AneuRx or aortic tube stent-grafts, respectively. Measurements were made relative to these absolute anatomic landmarks for concordant comparison of pre- and postdeployment scans. Whereas in practice this would provide an upper limit for stent-graft length, once the SP has been created, a surgeon or radiologist can refine device selection by assessing the SP to any desired point along the iliac artery that seems most appropriate for distal fixation.

The computer algorithm enabled automatic identification of the shortest luminal path by using the following procedure: Starting at the origin of the MLC path, the algorithm continuously steps one voxel closer to its goal, the farthest visible voxel along the path. Visibility between two voxels is defined as the condition of having a line segment between the two voxels that does not exit the lumen. However, to keep this path at least R away from the wall, a different neighboring voxel is chosen if the next voxel would be less than R away from the wall. In such a case, among the neighboring voxels that are closer to the goal, the one farthest away from the wall is chosen. The algorithm finishes when the last voxel on the path is reached. Finally, the same smoothing algorithm that was applied to the MLC paths is applied to the SP to smooth out the stair-steps that result from using integer coordinate voxel centers.

To simulate a commonly used digital subtraction angiographic measurement technique in which line segments are manually connected through the opacified arterial lumen on a workstation, we measured the two-dimensional length of the three-dimensional median centerline projected through four directions: anteroposterior, 45°; left anterior oblique, 45°; right anterior oblique; and lateral. These measurements were designated as projected MLC lengths. Measurements were performed by two authors (M.T. and K.P.) together. The maximum projected

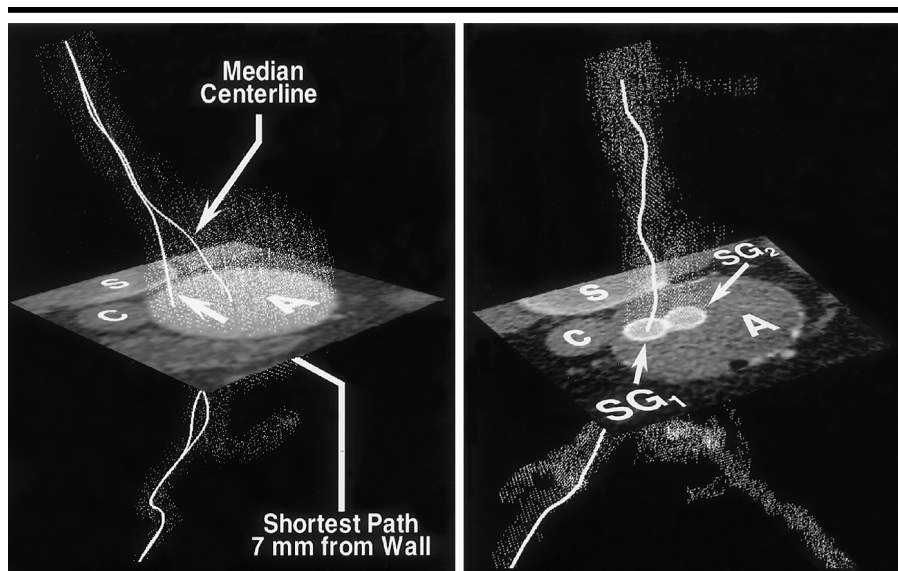


Figure 2. Left: CT scan data from a 56-year-old man with an AAA prior to stent-graft deployment, with three-dimensional representation of the contrast-enhanced lumen by using a point-cloud rendering. A single transverse reconstruction in the middle of the aneurysm is displayed with the aortic aneurysm (A), the inferior vena cava (C), and a lumbar vertebral body (S). The median centerline of the aortoiliac arterial flow lumen is indicated, as is the computer-derived SP, and is 173 mm from the most inferior renal artery to the right common iliac arterial bifurcation. The SP was selected to maintain a distance of at least 7 mm from the luminal wall because the right common iliac arterial diameter was 14 mm and measured 137 mm, a 36-mm difference. Right: CT scan of the same patient as in the image at left 1 day after deployment of an AneuRx arterial stent-graft. The aneurysm around the stent-graft has thrombosed. The primary stent-graft limb (SG_1) and the secondarily positioned contralateral limb (SG_2) also are indicated. The central axis (median centerline) of SG_1 is indicated by the white line through the point cloud of the residual aortoiliac arterial lumen. Note the similarity between the position of this path and that of the SP on the image at left. The length of this path served as the reference standard against which all other measurements were compared and was 139 mm long, indicating a 2-mm underestimation with the predeployment SP length measurement versus a 34-mm overestimation with the predeployment median centerline.

MLC was defined as the longest of the projected MLC measurements among the four projections in each patient.

IUW measurements ($n = 24$) were obtained during a planning conventional arteriographic study performed within 30 days before stent-graft deployment in 10 patients and at the time of stent-graft deployment in 14 patients. These measurements were part of routine patient examination before stent-graft deployment. The vascular surgeon (B.B.H.) who measured lengths was blinded to the predeployment CT measurements and stent-graft length and diameter. A 6.2-F 10–20-MHz intravascular US transducer and catheter assembly (Sonicath; Boston Scientific, Nantucket, Mass) was advanced over a 0.035-inch guide wire through an 8-F sheath to the supraceliac aorta and connected to a US scanner (CVIS; Boston Scientific). The tip of the intravascular US catheter was positioned at the inferior aspect of the lower main renal artery. A marker was placed on the catheter as it exited the groin. The catheter was with-

drawn until it reached the bifurcation of the common iliac artery ipsilateral to the side of anticipated primary component deployment. A second marker was placed on the catheter as it exited the groin, and the distance between the two markers was measured. These measurements were designated as IUW lengths.

Comparison of Measurement Methods

To determine the accuracy with which seven predeployment measurement techniques enabled prediction of stent-graft length, MLC, SP, projected MLC through each of four projections, and IUW measurements were compared with the length of the flow lumen through the primary component after the entire stent-graft was deployed. The MLC length of the stent-graft was measured on postdeployment CT angiograms from the most inferior main renal artery to the common iliac artery bifurcation of the primary site of stent-graft deployment and estab-

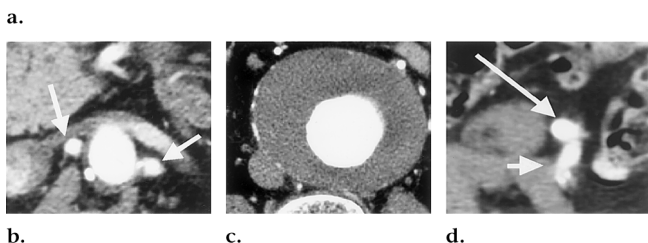
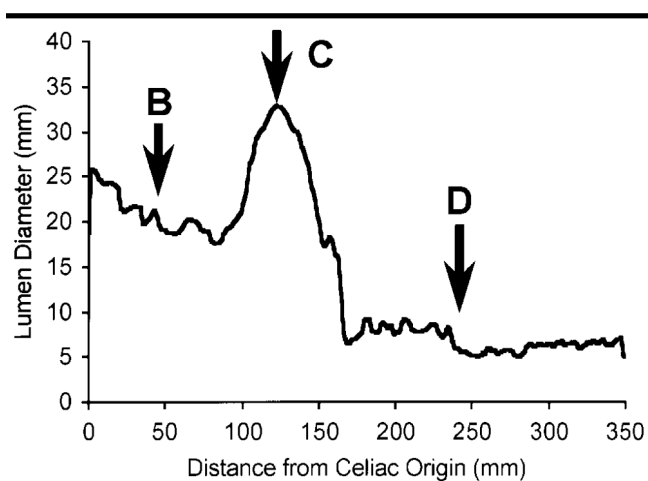


Figure 3. (a) Plot of the mean orthonormal luminal diameter versus position along the median centerline of the aorta and iliac arteries. This plot was automatically generated after the median centerline was identified. A cursor was moved along the plot, and corresponding transverse sections were displayed dynamically for exact identification of the origin and terminus of the distance measurements. (b, d) Branch points (B, D) were displayed as local peaks on the curve when the branches originated parallel to the orthonormal plane (renal arteries [arrows in b]) or as transitions in luminal diameter when oriented longitudinally (common to external [long arrow in d] and internal [short arrow in d] iliac arteries). (c) The maximum diameter on the plot (C) corresponds to a maximum mean luminal diameter of 33 mm, even though the outer wall of the aneurysm was more than 55 mm in diameter.

lished as the reference standard. M.T. and K.P. performed the measurements together, and M.T. performed the comparisons.

Finally, the MLC length of the stent-graft was measured and compared with the manufacturer's stated stent-graft length as further indication of the accuracy of the length measurements. One caveat to this measurement is the statement by the device manufacturers that the nominal device length may not correspond to the postdeployment length.

Differences between predeployment measurements and the reference standard were calculated for each patient. The predeployment measurement methods were compared relative to the reference standard by using one-way analysis of variance. Subsequently, Duncan multiple-range testing was applied to determine if significant differences existed between the individual predeployment

measurement methods. A *P* value of less than .05 was considered to indicate a significant difference. Pearson correlation was used to assess the effect of the maximum diameter of the AAA and the mean aortoiliac curvature on the percentages of difference between pre- and postdeployment length measurements.

RESULTS

Comparison of the postdeployment MLC stent-graft length and the manufacturer-stated stent-graft length revealed a mean difference of $-0.6 \text{ mm} \pm 3$. All measurements were within the manufacturers' tolerance for stent-graft length, 5 mm.

To assess the accuracy of stent-graft length prediction, the mean reference standard aortoiliac arterial length was $197 \text{ mm} \pm 18$. The mean predeployment aortoiliac SP, MLC, maximum projected

MLC, and IUW were $195 \text{ mm} \pm 18$, $207 \text{ mm} \pm 20$, $192 \text{ mm} \pm 19$, and $182 \text{ mm} \pm 19$, respectively, resulting in mean differences relative to the reference standard of $-2.1 \text{ mm} \pm 4.6$ ($P = .013$), $9.8 \text{ mm} \pm 6.8$ ($P < .001$), $-5.2 \text{ mm} \pm 7.8$ ($P < .001$), and $-14.1 \text{ mm} \pm 9.3$ ($P < .001$) for the four measurements, respectively (Fig 4). Analysis of variance results indicated that these measurement methods were significantly different from each other ($P < .001$). Duncan testing produced four significantly different groups of measurements. These four groups, in order of descending accuracy, were SP, MLC, maximum projected MLC, and IUW together with the four individual projected MLC measurements (ie, anteroposterior, lateral, and bilateral 45° oblique).

The performance of the various measurement methods relative to varying measurement tolerances from within 5, 7, 10, 12, and 15 mm of the reference standard result is presented graphically in Figure 5. This indicates a substantial advantage for SP measurements relative to all other measurement methods within a tolerance of 12 mm from truth. The performance of MLC approximated that of SP when tolerance was increased to 15 mm; however, both remained significantly better than projected MLC and IUW measurements. Examples of the performance of SP relative to that of MLC are illustrated in Figures 2 and 6.

In two patients, the SP resulted in underestimation of the postdeployment result by 17 and 12 mm (Fig 7). Image analysis revealed that stent-grafts conformed to the greatest aortic curve in these two patients.

To determine if MLC measurements are more reliable for some aortoiliac geometries, we correlated MLC measurements with the aortic luminal diameter and aortic tortuosity, quantified as the maximum curvature measured along the aortic MLC (12). The Pearson correlations of the percentage difference between pre- and postdeployment MLCs with maximum diameters of the AAAs and the mean aortoiliac curvatures were 0.21 and 0.26, respectively; this indicated either poor correlation between the size and curvature of the aortic lumen and the use of the MLC in predicting postdeployment luminal length or a sample size insufficient to establish a significant correlation. Although smaller (greater mural thrombus) and straighter aortic lumina may ultimately emerge as morphologic features conferring favorable stent-graft length predictions with MLC, our data do not establish this relationship.

The difference between the minimum and maximum aortoiliac projected MLC measurements among the four projections tested was 2–27 mm, with a mean of 14 mm ± 7 (Fig 8). The maximum projected MLC was obtained from an anteroposterior projection in two patients, from a 45° left anterior oblique projection in 13 patients, from a 45° right anterior oblique projection in eight patients, and from a lateral projection in 10 patients. No single projection enabled prediction of postdeployment aortoiliac arterial length as well as maximum projected MLC did (Fig 4).

DISCUSSION

On the basis of our analysis of aortic luminal displacement after stent-graft deployment, we predicted that an algorithm that could be used to calculate the SP could enable prediction of the stent-graft course through the aortic lumen more accurately than could traditional measurement methods. Our subsequent analysis in 33 additional patients established that the SP was significantly more accurate than were the MLC, projected MLC, and IUW for predicting luminal length after stent-graft deployment. Although the description of the algorithm for calculating the SP through the aortoiliac lumen may seem complex, it is critical for the clinician to understand that the implementation of this method is highly automated, which requires that the user merely identify the origin and terminus of the stent-graft, as well as the anticipated device diameter. With this information, the computer automatically calculates the path and path length.

Although validation of the clinical utility of the aforementioned measurement technique awaits prospective application in patients prior to stent-graft deployment, with device length determination based on the calculated SP, our data suggest that this measurement method has merit. Accurate stent-graft sizing may minimize complications related to inadvertently occluded aortoiliac branches, shorten the duration of the deployment procedure, and obviate expensive extension grafts when primary devices are too short for aneurysmal exclusion.

Although the SP measurement was superior to the other measurement methods in general, there were two patients in whom the SP resulted in underestimation of the postdeployment luminal length because the stent-graft followed the greater curve of the AAA. We were unable

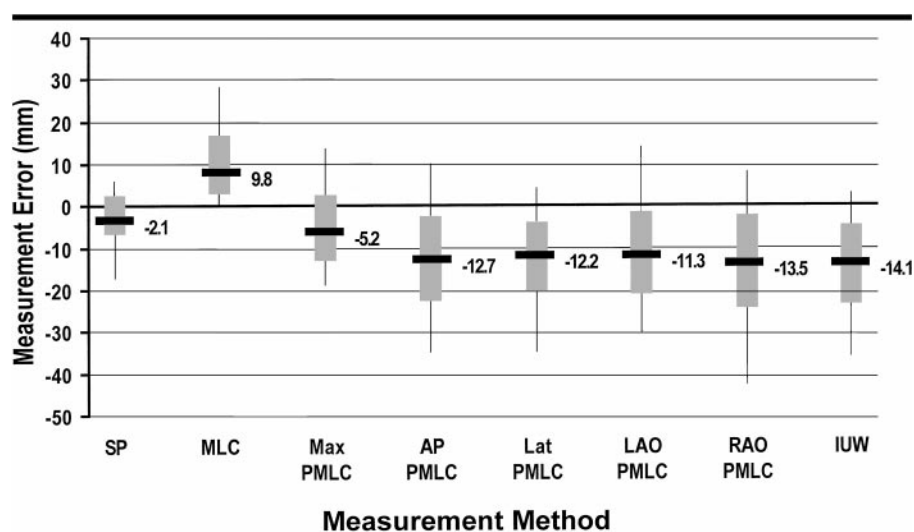


Figure 4. Graph shows a comparison of measurement methods and their absolute errors for predeployment aortoiliac lengths prediction relative to postdeployment lengths. Mean error is indicated by the black bar, with values expressed in millimeters to the right. The gray box indicates SD, and the whiskers indicate the highest and lowest error values. AP = anteroposterior, LAO = left anterior oblique, Lat = lateral, Max = maximum, PMLC = projected MLC, and RAO = right anterior oblique.

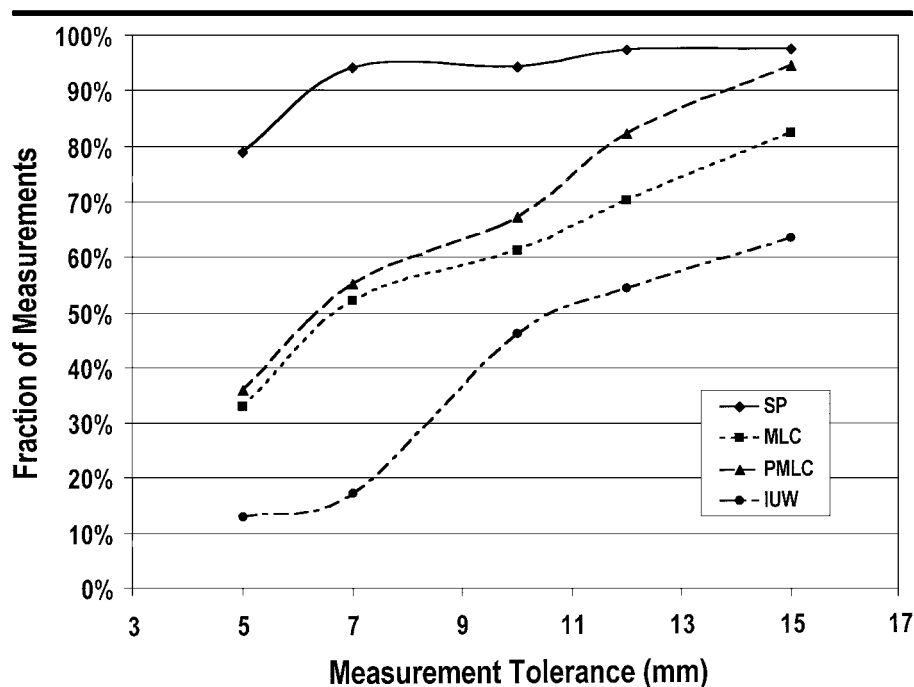


Figure 5. Graph shows percentage of all measurements for each measurement method (PMLC = maximum projected MLC) that are within varying tolerances of measurement accuracy indicated as being within 5, 7, 10, 12, or 15 mm of the luminal length after stent-graft deployment. For SP, MLC, and projected MLC, $n = 33$ patients; for IUW, $n = 24$ patients.

to identify any unique morphologic features associated with these aneurysms to explain the unusual course of the stent-graft; however, one possible explanation might relate to the use of excess longitudinal force on the delivery system at the time of deployment to make an oversized

device fit without occluding the internal iliac artery. In fact, this was confirmed in one of the two patients, in whom substantial longitudinal force was required to fit a stent-graft with a proximal end inadvertently deployed farther distal to the most inferior renal artery than was

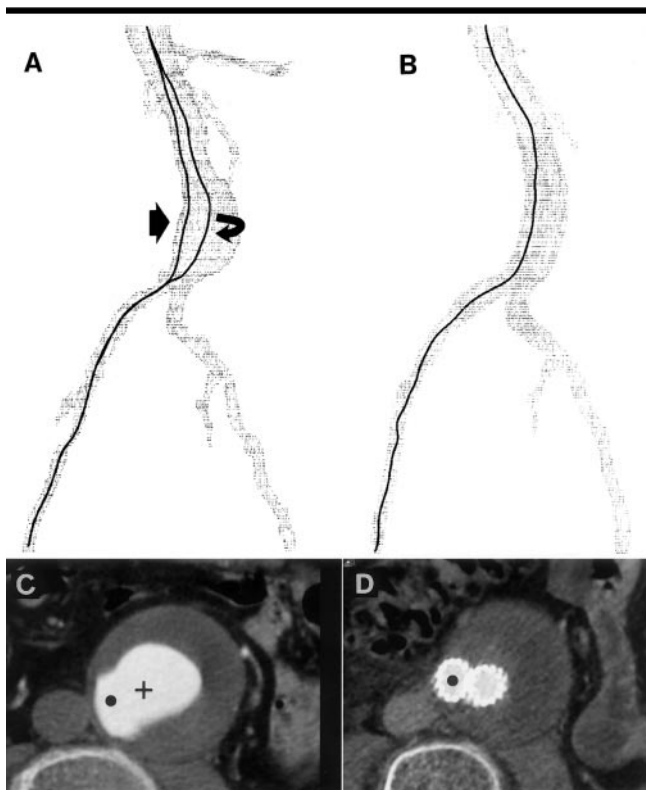


Figure 6. Helical CT angiographic data obtained before (A, C) and after (B, D) deployment of a bifurcated stent-graft in a 74-year-old man with AAA. A, Fifteen-degree right anterior oblique view of the segmented predeployment lumen shows the luminal SP (straight arrow) and the MLC (curved arrow) on the primary site of stent-graft deployment. B, Fifteen-degree right anterior oblique view of the segmented predeployment lumen of the device shows the MLC in the primary limb of the stent-graft. C, Transverse predeployment helical CT section through the AAA. • = luminal SP position within the flow lumen, and + = MLC position. D, Postdeployment transverse helical CT section through the AAA. • = MLC position in the primary limb of the bifurcated stent-graft. There is a high degree of concordance between the luminal SP of the predeployment data and the position of the primary limb of the stent-graft in the AAA. The SP and postdeployment measurements were identical in this case; however, the predeployment MLC was 11 mm longer than the postdeployment length.

intended into the aortoiliac lumen without occluding the internal iliac artery. Although we did not assess the effect of atheromatous and calcified plaques of the iliac arteries on the course of a stent-graft, its evaluation may be important in further refining the preprocedural prediction of device course.

MCL has been proposed as a preferred method for measuring aneurysmal length prior to stent-graft repair (8,12,16). To our knowledge, these measurements have not been formally validated in vivo. In the current study, the MLC enabled prediction of postdeployment luminal length in 33%–82% of patients within 5–15 mm of truth, respectively, with overestimation of stent-graft length by a mean of 10 mm. This decrement in accuracy relative

to SP was likely because the stent-grafts that we examined tended to follow the shortest distance through the lumen from proximal to distal fixation, with a mean MLC displacement of more than 8 mm between pre- and postdeployment measurements.

Recent software developments have allowed angiographers to measure distances along the curved course of opacified arterial lumina on digital images. Although a seemingly compelling tool for measuring luminal lengths, the method is highly limited by foreshortening of the complex arterial lumen once projected onto a two-dimensional display (17). To understand this phenomenon quantitatively, we simulated this measurement method by projecting the three-dimensional

MCL from CT through four commonly acquired projections. Because overestimation of the true MLC is geometrically impossible on the basis of measurement of a two-dimensional projection, we hypothesized that the maximum projected MLC would be closest to truth. In fact, we found that the maximum projected MLC enabled prediction of postdeployment length in 36%–94% of patients within 5–15 mm of truth, respectively, resulting in underestimation of length by a mean of 8 mm in 27 patients and overestimation of length by a mean of 8 mm in six patients.

It is interesting to note that the view angle that provided the most accurate projected MLC was not consistent among the cases studied; therefore, one cannot rely on a specific projection to provide the least foreshortened representation of the arterial lumen. However, on the basis of the results of the current study, the anteroposterior projection is the least reliable for measuring projected luminal length, since it provided maximum aortoiliac length in only two patients. This observation is likely attributable to the anteroposterior curvature of the iliac arteries, which caused foreshortening in the frontal plane.

Rotational angiography, which enables acquisition of multiple projections about an axis of rotation, may facilitate finding a projection that minimizes luminal foreshortening; however, to our knowledge, the measurement of true three-dimensional paths has not been demonstrated. The degree of underestimation resulting from projected MLC measurements was less than might have been expected because of the compensatory overestimation of lengths that follow the luminal centerline. Our measurement of projected MLC does not fully represent the limitations of length measurements from true projectional arteriographic data, since we did not simulate additional errors caused by magnification and parallax. Parallax error has been shown to influence length measurements to a high degree; even within a small fluoroscopic field it can exceed 4 cm (18).

It is interesting to note that aortoiliac arterial length measurements based on projectional arteriography have been reported to correspond well to hand-drawn MCLs obtained at CT (8). However, in tube-graft placement candidates, angiographic length measurements exceeded MCLs, whereas in bifurcated graft placement candidates, the opposite was true. The authors (8) attributed this finding to arching of the catheter in the aneurysmal

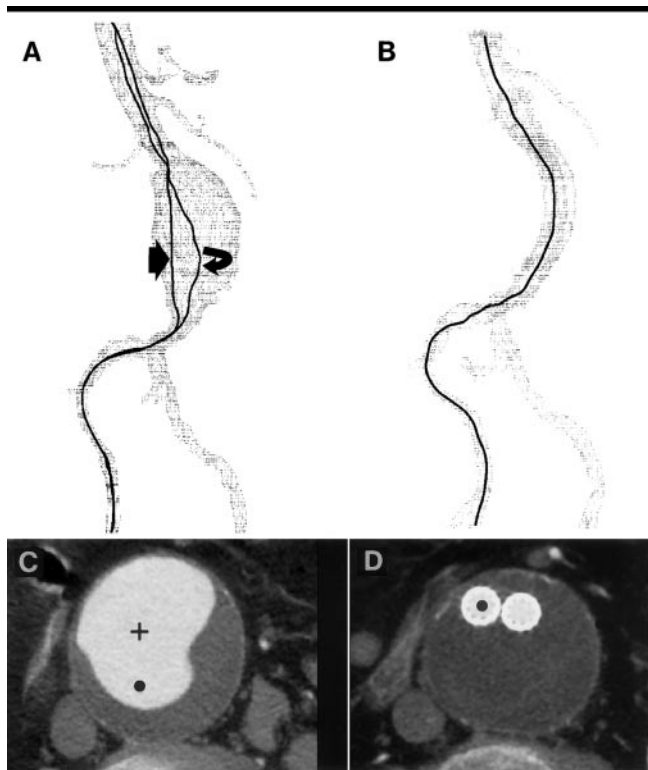


Figure 7. Helical CT angiographic data obtained before (A, C) and after (B, D) deployment of a bifurcated stent-graft in a 66-year-old man with AAA. A, Forty-five-degree right anterior oblique view of the predeployment lumen shows the luminal SP (straight arrow) and the MLC (curved arrow) at the primary site of stent-graft deployment. B, Forty-five-degree right anterior oblique view of the postdeployment lumen of the device shows the MLC in the primary limb of the stent-graft. The course of the primary limb is closer to that of the median centerline path than to the luminal SP. C, Predeployment transverse helical CT section through the AAA. ● = luminal SP position within the flow lumen, and + = MLC position. D, Postdeployment transverse helical CT section obtained through the AAA. ● = MLC position within the primary limb of the bifurcated stent-graft. The shortest luminal length resulted in 17-mm underestimation of the postdeployment length because the stent-graft took an unusual course along the greater aortic curve. This patient, along with another in whom the SP was used to underestimate the postdeployment length by 12 mm, were the only two patients whose predeployment length predictions were not within 7 mm of the postdeployment length.

sac, whereas shortcuts of the catheter in the curves of the tortuous iliac arteries compensated for length overestimation. An important limitation of that study (8) was the absence of a reference standard result; the investigators did not correlate predeployment aortoiliac lengths with postdeployment lengths, substantially limiting the utility of their results. In addition to lesser accuracy in predicting stent-graft length, conventional arteriography is limited because it may not demonstrate the extent of aneurysmal disease and abnormal vessel wall changes (9,10,19).

An even more recent advance that overcomes the limitations of projection, parallax, and magnification is the use of

graduated guide wires and catheters to measure luminal lengths. Unfortunately, these catheters were not routinely used at the time of patient imaging for this study; therefore, we cannot ascertain the accuracy of measurements made with this technique relative to those made with the other techniques assessed. Nevertheless, one may glean insight into the performance of this method by examining our results for IUW, which should provide similar measurements to those derived with graduated catheters if it is safe to assume that the course of the

graduated catheter within the arterial lumen is similar to that of an intravascular US catheter.

Aortoiliac IUW measurements enabled prediction of postdeployment length in 13%–63% of patients within 5–15 mm of truth, resulting in underestimation of length by a mean of 15 mm in 23 patients and overestimation of length by 3 mm in one patient. This underestimation tendency was likely due to the tendency of the intravascular US catheter to follow the SP through the aorta and iliac arteries but did not compensate for the stent-

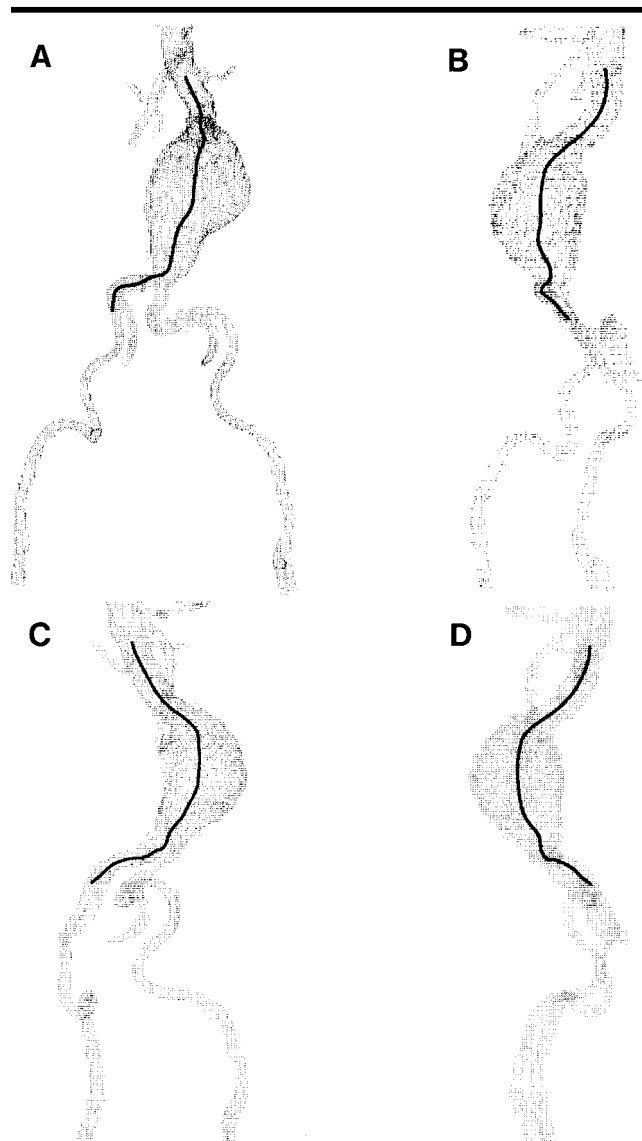


Figure 8. Helical CT angiographic data obtained before deployment of a bifurcated stent-graft in an 82-year-old man with AAA. A, Frontal; B, 45° right anterior oblique; C, 45° left anterior oblique; and D, lateral MLC projections obtained before deployment are shown. Luminal lengths vary substantially. Absolute errors of the measured lengths were -13, -27, 0, and -13 mm for the four view angles, respectively.



Figure 9. Helical CT images obtained with an intravascular US catheter (arrows) within the lumen of an aneurysmal aorta in a 72-year-old man. Left: Transverse reconstruction. Right: 20-mm-thick sagittal maximum intensity projection image. The catheter was inserted into the right femoral artery. These views demonstrate why IUW measurements tend to result in underestimation of the length of the path that the stent-graft will follow, since the catheter tends to lie against the wall of the aortic lumen and take a straighter course through the aorta than would a stent-graft, which has a substantially larger diameter and thus must lie in a position placing its median axis at least one radius away from the luminal wall.

graft radius (Fig 9). These findings are consistent with the results of an in vitro study of AAA (10), in which investigators observed that the distance between the major side branches and aortic bifurcation was larger for external measurements than for those obtained with intravascular US. Our findings further support the conclusion that stent-graft sizing with IUW is inaccurate (17,20).

An important limitation of this study is that our results cannot be generalized to all stent-grafts. Although the SP enabled accurate prediction of the appropriate stent-graft length for 31 AneuRx and two Excluder stent-grafts, further investigations are required to establish the generalizability of these results to other devices. It is possible that stent-grafts might be developed that do not follow the SP. Finally, the clinical utility of SP measurement cannot be determined until the outcomes of a cohort of patients with AAAs treated with stent-grafts prospectively sized on the basis of predeployment SP measurements can be studied.

In conclusion, our study findings demonstrated that for the AneuRx and Excluder devices studied, the shortest aortoiliac path length that maintained at least one common iliac arterial radius

from the vessel wall enabled prediction of stent-graft length significantly more accurately than did MLC, maximum projectional arteriography, and IUW measurements. By assuming accurate stent-graft delivery, this potentially allows for a tolerance of 5 mm at the proximal and distal fixation sites.

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