Computed tomography-based anatomic characterization of proximal aortic dissection with consideration for endovascular candidacy

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Background: **Proximal aortic dissections are life-threatening conditions that require immediate surgical intervention to avert an untreated mortality rate that approaches 50% at 48 hours. Advances in computed tomography (CT) imaging techniques have permitted increased characterization of aortic dissection that are necessary to assess the design and applicability of new treatment paradigms.**

Methods: **All patients presenting during a 2-year period with acute proximal aortic dissections who underwent CT scanning were reviewed in an effort to establish a detailed assessment of their aortic anatomy. Imaging studies were assessed in an effort to document the location of the primary proximal fenestration, the proximal and distal extent of the dissection, and numerous morphologic measurements pertaining to the aortic valve, root, and ascending aorta to determine the potential for an endovascular exclusion of the ascending aorta.**

Results: **During the study period, 162 patients presented with proximal aortic dissections. Digital high-resolution preoperative CT imaging was performed on 76 patients, and 59 scans (77%) were of adequate quality to allow assessment of anatomic suitability for treatment with an endograft. In all cases, the dissection plane was detectable, yet the primary intimal fenestration was identified in only 41% of the studies. Scans showed 24 patients (32%) appeared to be anatomically amenable to such a repair (absence of valvular involvement, appropriate length and diameter of proximal sealing regions, lack of need to occlude coronary vasculature). Of the 42 scans that were determined not to be favorable for endovascular repair, the most common exclusion finding was the absence of a proximal landing zone (n = 15; 36%).**

Conclusions: **Appropriately protocoled CT imaging provides detailed anatomic information about the aortic root and ascending aorta, allowing the assessment of which dissections have proximal fenestrations that may be amenable to an endovascular repair. (J Vasc Surg 2011;53:942-9.)**

Aortic dissections involving the ascending aorta are life-threatening conditions frequently requiring immediate surgical intervention. Historically, untreated proximal aortic dissections are associated with a mortality rate approaching 50% at 48 hours.[1] In the faces of advances of medical, surgical, and endovascular treatments, treatment strategies have changed, and the relevance of older results may be questioned.

The current dogma of the surgical management includes resection of the primary intimal tear, reconstruction of the aortic root if involved (preserving coronary flow and aortic valve function, which may require valve repair or replacement), and restoration of flow into the distal true lumen.[2,3] Optimal techniques used in open surgical repair include axillary artery cannulation,[4,5] adjunctive cerebral perfusion,[6,7] and the deep hypothermic circulatory arrest.[8-10] Although some surgeons have advocated extended repairs involving the aortic arch, others prefer a strategy that minimizes the potential for complications by limiting circulatory arrest time and procedural complexity.[11,12]

Despite new surgical advances, the surgical mortality rates for repair of proximal aortic dissections range from 11% to 26% and vary considerably by the center performing the repair.[2,12-15] A small number of case reports[16-18] have described endovascular methods to treat proximal aortic dissections, but no extensive series, comparative studies, or even intermediate outcomes exist.

The current understanding of the pathophysiology of aortic dissection involves the development of an intimal tear, allowing blood to split the medial layer of the aortic wall and creating a false lumen. Most cases of aortic dissection are associated with a definable intimal tear, which is most commonly transverse. The most common location for the intimal tear is ≤3 cm of the coronary arteries. Once present, the false lumen of the aortic dissection may extend proximally, often into the noncoronary sinus, distally into the aortic arch and beyond, or in both directions. Recent imaging advances, with respect to temporal resolution, spatial resolution, and postprocessing algorithms, have provided a means to further characterize the detailed anatomy of aortic dissections. Such information may be used to determine the extensiveness of the required surgical intervention as well as assess the potential for the ability to treat

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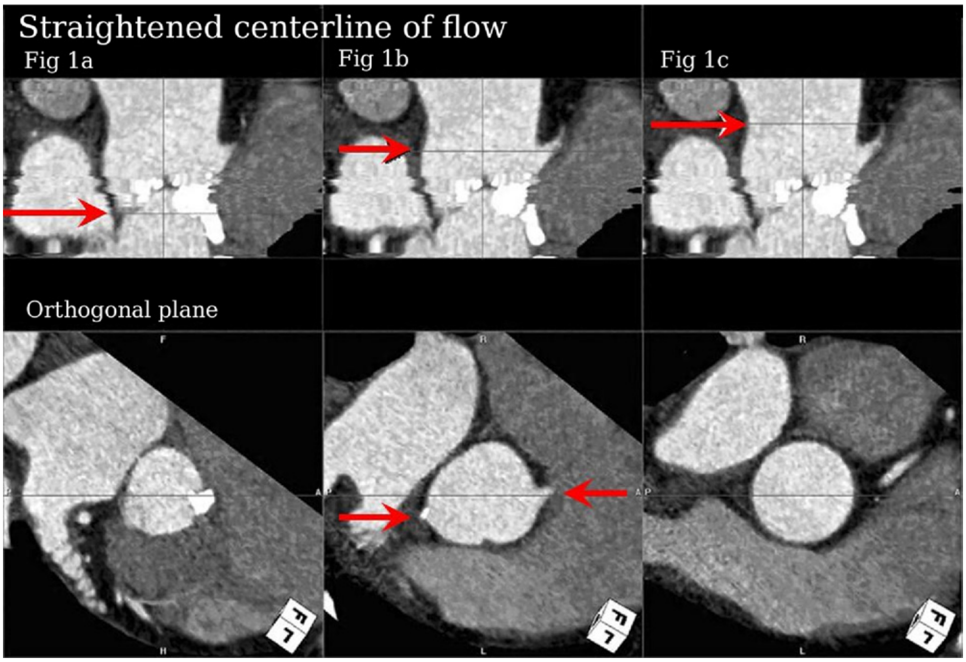

Fig 1. Top row, A centerline reconstruction and **(bottom row)** orthogonal planes of a patient with a proximal reconstruction highlighting the various measurements recorded. The orthogonal plane refers to a plane perpendicular to the centerline at any point. **Panel a** demonstrates the aortic annulus in both a centerline reconstruction (*red arrow*) and orthogonal plane. **Panel b** similarly demonstrates the coronary arteries (*red arrows*), and **Panel c** shows the sinotubular junction (*red arrow*).

such situations with an endovascular approach. The objective of this study was to perform a computed tomography (CT)-based characterization of proximal aortic dissection, report basic imaging requirements, and define novel anatomic relationships pertaining to potential endovascular candidacy.

METHODS

All patients presenting with acute proximal aortic dissections to our institution between 2004 and 2006 with preoperative electrocardiogram (ECG)-gated digital CT data (using hyperosmolar contrast, unless contraindicated) were analyzed. CT scans were performed on a 16-row scanner at 55% of the RR interval or on a 64-row scanner at 70% of the RR interval, both using a 1.2-mm collimation (Siemens, Erlangen, Germany). Bolus tracking of the descending aorta (target of 120 to 150 HU) was used to optimize the quality of the studies. Isoosmolar contrast was used in some cases in which patients had pre-existing renal dysfunction.

Interpretation of CT scan. All ECG-gated CT image files were uploaded to a Terarecon workstation and analyzed with an Aquarius Workstation (Terarecon, San Mateo, Calif). Patients with CT data that were not interpretable were excluded from further analysis. These included noncontrast studies, studies that did not include the entire ascending aorta, and those in which the contrast bolus was poorly timed. Special note was taken of the cohort who had prior cardiac surgery in an attempt to discern any association between prior cardiac operations and the location or extent of the dissection or association with involvement of the aortic root.

A semiautomated algorithm was used to reconstruct a centerline of flow through the true lumen of the ascending aorta, aortic arch, and proximal descending thoracic aorta. All measurements were made based on the centerline of flow,[19] and when centerlines of flow could not be properly reconstructed, measurements were made using manual three-dimensional techniques to create orthogonal planes to the area of interest (Fig 1). Short- and long-axis measurements were determined. The following definitions were used to provide a uniform interpretation of radiographic information:

1. The aortic annulus was defined as the junction between the left ventricular outflow tract and the ascending aorta at the level of the attachment of the aortic leaflets to the aortic wall (Fig 2).
2. The sinotubular junction (STJ) was defined as the point at which the sinus of Valsalva becomes the tubular ascending aorta (Fig 2). In aneurysms or dilatation involving the aortic root and proximal ascending aorta, the STJ was not always identifiable. The STJ served as the zero point for the aorta, thus all longitudinal measurements distal to the STJ are expressed as positive

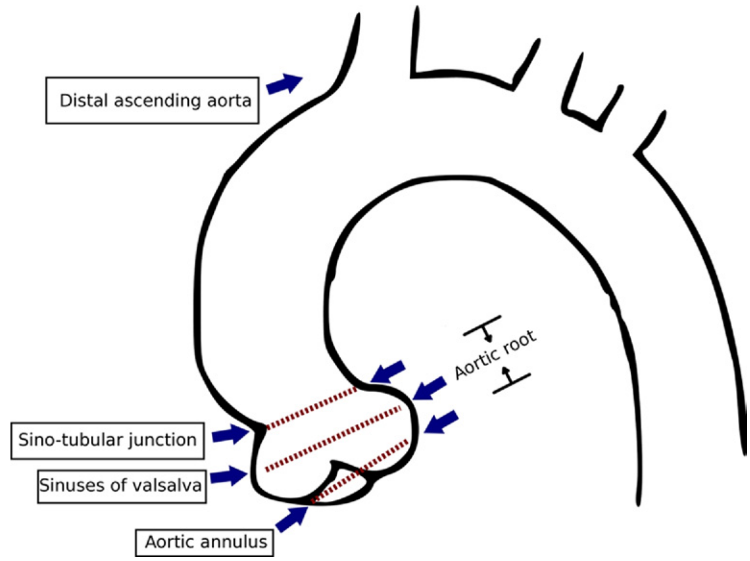

Fig 2. Schematic of aortic root and ascending aorta demonstrates the location of the aortic annulus, the sinuses of Valsalva, the sinotubular junction, and the distal ascending aorta.

distances, whereas those proximal to the STJ are expressed as negative distances.

3. The aortic root was defined as the most proximal portion of the aorta originating at the aortic annulus proximally and extending distally to the STJ (Fig 2). When the STJ was effaced, this point was not measured. The distal aorta was defined as being the region just proximal to the origin of the innominate artery.
4. The intimal tear was determined by the presence of a clear region of intimal disruption and evidence of contrast within the aortic wall above or below the defined tear, or both.
5. Intimal tear location was defined in terms of distance from the proximal aspect of the tear to the STJ (with negative values ascribed to tears originating proximal to the STJ), whereas the distal tear location was measured with respect to the innominate artery. In addition, the aorta was divided into quarters, including the greater curvature, lesser curvature, and anterior and posterior segments. The location of the primary tear was classified into one of these four quadrants.
6. The STJ was assessed with respect to the coronary arteries. The distance between the highest and lowest (nonsurgically altered) coronary vessels was measured from the STJ. The distance between the STJ and the highest discernible point of the aortic valve was also recorded.
7. The maximal aortic diameter was assessed from images reconstructed with a centerline of flow based on the true lumen. The distance from the STJ to the point of maximal aortic diameter was also measured.

The following criteria were used to define potential suitability for endograft insertion: presence of a proximal landing zone (STJ $\leq$ 38 mm), fenestration distal to the STJ, minimum distance between intimal fenestration and STJ $\geq$ 10 mm, and absence of coronary bypass grafts originating from the ascending aorta.

A proportion of the CT scans were read by two independent reviewers and measurements were compared to assess variability. Discrepancies were minimal due to the standardized centerline of flow techniques used, thus we did not have two independent reviewers assess each of the scans.

Statistics: Statistical analysis was performed using S-Plus 7.0 software (Insightful, Wash). Results are represented as the mean ± standard deviation. The Fisher exact test for two-by-two tables was used for assessment of associations. Correlation was tested using the Pearson correlation. Results were considered statistically significant with a value of $P < .05$.

RESULTS

During the 2-year study, 162 patients presented to the Cleveland Clinic with the diagnosis of a proximal aortic dissection (Fig 3), and 86 underwent emergent repair of their proximal aortic dissection without preoperative CT imaging at our institution (based on findings from transesophageal echocardiography or by CT scans from another hospital). Preoperative CT scans of the proximal aorta were performed before surgical intervention in the remaining 76 patients, who were a mean age of 59 ± 14 years. These scans were considered suboptimal in 17 patients as a result of lack of contrast, suboptimal contrast timing, or limited scan coverage. However, usable data from suboptimal scans were included in the overall data set, supplementing the complete data from the 59 patients with optimal scans. The quality of 59 scans (77%) was adequate to allow assessment of anatomic suitability for treatment with an endograft.

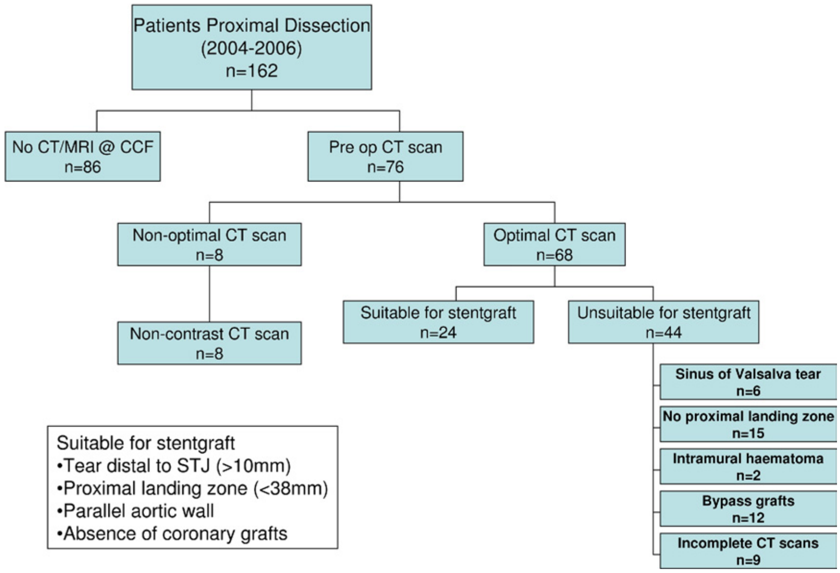

Fig 3. Flow chart shows the distribution of patients presenting with diagnoses of proximal aortic dissection to the Cleveland Clinic Foundation (*CCF*) between January 2004 and December 2006 based on clinical history and preoperative diagnostic assessment. *CT,* Computed tomography; *MRI,* magnetic resonance imaging; *STJ,* sinotubular junction.

Table I. Location of intimal fenestration

	Aortic root	*Ascending aorta*			*Aortic arch*	
	Total	*Prox*	*Mid*	*Distal*	*Arch*	*Dist arch*
Total	26	30	23	33	32	22
	7	Aortic root fenestration				
	19	Retrograde dissection into aortic root				

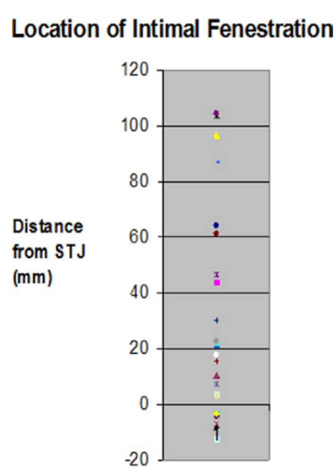

Fig 4. The location of the intimal fenestration is plotted as the distance from the sinotubular junction (*STJ*) in millimeters. The point of the sinotubular junction is set at 0 mm, thus negative values represent intimal fenestrations within the aortic root.

Patients with a history of cardiac surgery more commonly underwent preoperative CT imaging than those without prior cardiac operations (58% vs 35%).

Computed analysis of aortic dissection plane and location. The dissection plane was identified in all of the contrast-enhanced studies (68 of 76 studies). The dissection plane was not identified in eight studies because the CT scans were not contrast enhanced in six patients and because flow was absent in the presumed dissection plane and with the diagnosis of an intramural hematoma in two patients. Of the 68 cases in which dissection planes were noted, 26 (38%) involved the sinus of Valsalva, 19 as a result of retrograde propagation of a more distal tear, and seven appeared to originate within the aortic root (Table I).

A single precise intimal fenestration was identifiable in 28 of the 68 patients (41%), of which 21 (75%) were located 32 ± 29.2 mm distal to the STJ. In five patients, the tear was located distal to the origin of the innominate artery, thus originating within the aortic arch. In one patient, multiple intimal tears were noted within the ascending aorta. Seven patients presented with tears distal to the left subclavian with retrograde extension into the proximal ascending aorta. In each of these patients, the intimal tear was identified within the descending thoracic aorta (Fig 4). When the tears occurred within the ascending aorta or aortic arch, they most commonly were located along the greater curvature of the aorta (66%), with the minority occurring along the lesser curvature (14%), anteriorly (10%), or along the posterior aorta (10%; Fig 5). There was no correlation between the location of the intimal fenestration and the diameter of the STJ, diameter of the distal ascending aorta, the length of the ascending aorta, or the

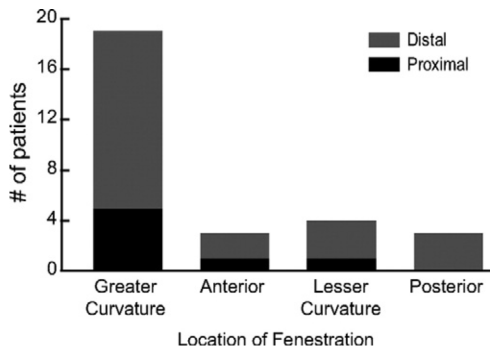

Fig 5. The aorta was subdivided into quarters: greater curvature, lesser curvature, anterior, and posterior. Intimal fenestrations were identified as being proximal to the sinotubular junction (*blue*) or distal (*purple*). Most of the intimal fenestrations were located on the greater curvature.

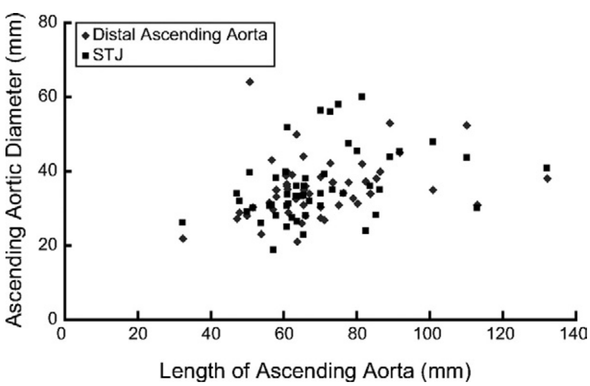

Fig 6. A scatter plot shows the diameter vs length of the ascending aorta diameter at the sinotubular junction (*STJ*) and distal ascending aorta levels.

maximal ascending aortic dimension, when assessed using the Pearson correlation.

Aortic root. In proximal dissections with intimal tears originating within the aortic root (proximal to the STJ), the average distance from the STJ to the highest coronary artery orifice was −12.5 ± 3.7 mm and was −17.8 ± 3.7 mm to the lowest coronary orifice. When tears were located distal to the STJ, the average distance from the STJ to the highest coronary artery orifice was 11.6 ± 7.2 mm and was 18.3 ± 8.1 mm to the lowest coronary orifice. The coronary orifices ranged from 5.1 to −41.6 mm proximal to the STJ. The average distance from the STJ to the aortic valve in the center of the aorta was 18.5 ± 7.6 mm, (range, 10-42.4 mm). There was no difference when groups were compared based on location of the intimal fenestration ($P > .05$). The average STJ diameter was 36.0 ± 9.4 mm (range, 18.9-60.0 mm).

Ascending aorta. The average length of the ascending aorta was 70.5 ± 18.0 mm (range, 32-132 mm; Fig 6). The diameter of the distal ascending aorta, measured immediately proximal to the innominate artery was 35.7 ± 8.1 mm (range, 21-64.1 mm). The maximal diameter of the ascending aortic averaged 45.7 ± 18.0 mm (range, 20.7-115 mm). The longitudinal location of the maximal ascending aortic dilation was 22.0 ± 22.6 mm distal to the STJ, although in some cases, the maximal aortic dimensions were within the sinus of Valsalva proximal to the STJ.

History of cardiac surgery. A history of cardiac surgery was present in 44 of 76 patients (57.8%), and the type of procedures is summarized in Table II. There was no association between the location of the dissection plane and the history of cardiac surgery when examined by Fisher exact test ($P > .05$) for a dissection plane involving the aortic root, ascending aorta, or aortic arch. No correlation was found for the extent of the dissection and a history of cardiac surgery ($P > .05$).

Suitability for endovascular intervention. The assumed criteria for suitability of an endovascular intervention are listed in Table III. There were 24 patients who were deemed suitable based on the anatomy of the ascending aorta and the anatomic characteristics of the proximal dissection for a potential endovascular repair. The presence of coronary bypass grafts originating off of the ascending aorta was considered a contraindication for consideration of a theoretic endovascular repair.

Table II. Details of procedures in 44 patients with a history of cardiac surgery

Procedures	*No. (N = 44)*
Coronary bypass grafting	3
Aortic valve replacement	8
Replacement of ascending aorta	27
Aortic arch replacement	7
Combined cardiac procedures	22

Table III. Criteria for suitability of an endovascular intervention

- Proximal landing zone (sinotubular junction ≤38 mm)
- Fenestration distal to sinotubular junction
- Minimum distance between intimal fenestration and sinotubular junction ≥10 mm
- Absence of coronary bypass grafts originating from ascending aorta

DISCUSSION

We used centerline flow analyses to assess proximal aortic pathology in this study in an effort to report imaging requirements and characterize basic anatomic relationships of type A dissections that may facilitate alternative treatment options. Centerline flow analysis had been previously described by our group and applied to the assessment of thoracic stent graft migration.[19] The optimal imaging study for assessing the dissection anatomy is an ECG-gated CT scan reconstructed at 55% or 70% of the RR interval (based on the type of CT scanner) to minimize motion artifact in the ascending aorta. The aortic valve, during this segment of the cardiac cycle, would be only partially opened (diastole occurs at 80% of the RR interval). Recent advances have allowed for four-dimensional CT studies at an even higher temporal resolution (<80 msec) and may yield additional information; however, such techniques are not typically performed in emergency situations. Furthermore, significant differences exist between patients who have undergone prior open chest procedures with regard to morphologic changes throughout the cardiac or respiratory cycle, yet large numbers of patients are required to define these differences given the broad range of anatomies associated with proximal dissections.

No commercially available endovascular treatment modalities currently exist. Several cases or small series have been reported[16-18] yet lack convincing evidence of a broadly applicable method of treatment. The improvements in imaging with respect to spatial resolution (thin collimation with fast gantry speeds) coupled with advances in temporal resolution (dual-source CT scan) have provided a means for a detailed interrogation of the aorta during any phase of the cardiac cycle.[16-18,20] Morphologic characteristics can be aptly defined and provide cause for speculation of a means to identify a subset of patients that may be amenable to endovascular repair.

Akin to open surgical objectives, there must exist a means to seal the primary fenestration, limit distal false lumen flow, and prevent retrograde propagation of the dissection should an endograft treatment be considered. Further extension of an endovascular repair into the arch is feasible in the absence of circulatory arrest, but the ability to accomplish the primary treatment objectives in the setting of acute proximal dissections is questionable.

Clearly, good results relate to the selection of appropriate patients with anatomy that will allow for proper sealing of the false lumen with a limited risk of proximal extension into the aortic root. The potential for success with an endovascular strategy requires detailed knowledge of the dissection, appropriately sized endovascular devices, and companies willing and interested in the production of devices for such applications. The information required for such an analysis is only obtainable from high-resolution ECG-gated CT.[21-24]

Advances in image acquisition and processing have relegated prior studies refuting the inaccuracy of CT identification of fenestrations and flaps[23] to be historical. Recent reports indicate that sensitivity and specificity rates for dissection diagnosis and flap identification exceed 82% and 100%, respectively.[24] Our analysis showed that false lumen identification was possible in all patients undergoing CT analysis, and the diagnosis was confirmed in all patients who underwent surgical repair.

The mere identification of a false lumen is not sufficient when considering alternative treatment strategies, however, the precise location of the primary fenestration is required in addition to details about the morphology of the aorta proximal to the dissection origin. During our analysis, we were only able to incontrovertibly identify a primary fenestration in 43% of the patients, which is lower than other reports (82% of the cases),[24] but we were able to determine the presence or absence of root involvement in all patients. When the intimal injury was identified in our series, the average length of the tear was 17.9 ± 15.3 mm. This implies that tears are relatively short and most were located along the greater curvature about 2 cm above the STJ. Therefore, most patients would be endovascular candidates if the objective were to simply seal the primary fenestration from within the true lumen.

However, if the fundamental principles of both open and endovascular surgery are adhered to, where a repair should be initiated at the level of "normal" aorta, the number of anatomically acceptable endovascular candidates would markedly diminish as a result of retrograde propagation of the dissection plane. The aortic diameter at the level of the STJ and innominate arteries averaged 36 mm. In contrast, the mean maximal aortic diameter was 45 mm, and the dilatation was most frequently located between the STJ and innominate artery. This is consistent with the most common conventional repair for acute proximal dissections of ascending aortic placement from the STJ to the proximal arch. However, the proximal neck length, which would be used for both fixation and sealing of an endovascular device is not generous. Although most primary fenestrations were distal to the STJ, most were ≤20 mm of the STJ. Given that 20 mm of fixation and sealing is required for most thoracic endovascular devices, the ability of such a device to establish a seal within the proximal aorta remains speculative (Fig 4).

Finally, one must also consider the relationship of the STJ (presumably the point of optimal proximal fixation and sealing of an endovascular device) with the critical root structures. The average distance between the STJ and coronary artery orifice was 12 to 18 mm, and the distance from the STJ to the tip of the aortic cusps was approximately 18 mm as well. These measurements have implications for proximal device design. There is a tendency to use uncovered nitinol stents in many thoracic devices to prevent fabric infolding and optimize deployment in many circumstances. Such a practice for ascending aortic devices must be questioned given the potential for valvular compromise coupled with the likely failure of apposition of such stents to the wall of noncylindrical aortic root.

In an effort to look at specific subsets of patients in this study, we attempted to assess relationships between baseline aortic diameters and the longitudinal position of the intimal tear (Fig 7). This approach is intended to assess patients that would be excluded from endovascular consideration. For example, it makes no sense to consider such an endovascular repair in patients with significantly abnormal roots (large diameter), dysfunctional aortic valves, or patent bypassed coronary arteries originating from the dissecting ascending aorta. Thus, several morphologic characteristics must be met to even consider such a treatment, and device designs should focus on such patients (lower right quadrant of Fig 6).

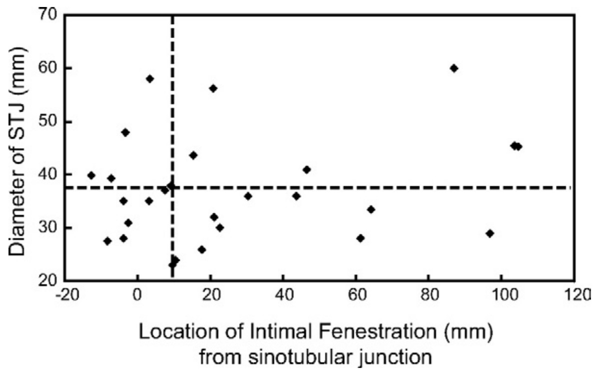

Fig 7. A *scatter plot* shows the location of the intimal fenestration vs the diameter of the sinotubular junction (*STJ*). The distance of the intimal fenestration is represented in millimeters relative to the STJ (x axis), and the diameter of the STJ junction is shown on the *y* axis in millimeters. The *dashed lines* on the x axis at +10 mm distal to the STJ and at 38 mm on the y axis represent the minimum distance required to have a proximal landing zone and the maximum aortic size based on available stent grafts, respectively. The *lower right hand corner* represents the potential cases identified by computed tomography that may be amenable to a stent graft repair of a proximal aortic dissection based on anatomic characteristics. Patients in the *upper* and *lower left quadrants* have unfavorable anatomy based on the location of the intimal fenestration, that is, <10 mm from the STJ or within the aortic root (proximal to the STJ). Patients located in the *upper right quadrant* are identified as having an intimal fenestration >10 mm from the STJ, but the aortic diameter is excessively large.

The length of the ascending aorta also merits discussion when considering device design options. The average length in this series was 70 mm, which is markedly shorter than all devices used for conventional repair of descending thoracic aortic aneurysms. Thus, shorter devices are required, with the understanding that such devices must be accurately deployed proximally at the STJ as well as distally proximal to the innominate artery. There were no statistically significant relationships between STJ diameter, ascending aortic length, and fenestration location, implying that each anatomic measurement must be assessed independently and then viewed concurrently to establish the feasibility of an endovascular repair.

Deployment characteristics must also be considered. To ensure aortic apposition at the level of the STJ, devices will have to be introduced through the aortic valve. In the setting of stenotic or relatively normal valves, this is not an issue; however, the procedure would result in considerable risk in patients with mechanical valves or older biologic valves. Challenges noted within the aortic arch, where some stent grafts tend to sit proud as a result of inadequate apposition to the lesser curvature, may be repeated in the proximal aorta. Given the marked difference in ascending aortic length between the lesser and greater curvature, attention must be directed to how the devices will sit within the aorta after deployment. There exists a significant potential for iatrogenic injury in this region, and caution must be emphasized.

Patients who have undergone prior cardiac surgical procedures, who comprised almost 60% of the patients in our series, merit some specific discussion. Given the potential for differences in the propagation patterns of aortic dissection in patients with prior cardiac surgery, we assessed our patients for potential differences, particularly the potential for the "protective effect" scar tissue may provide with regard to proximal extension. However, we could not identify any association between the extent and location of the aortic dissection in these patients.

This study is obviously limited by the number of patients analyzed and the characteristics specific to the patient population referred to our institution. The statistical associations between various anatomic characteristics appear to be less important than the context by which the composite morphologic measurements are viewed. We analyzed these data with the understanding that endovascular repair of dissections with primary fenestrations within the ascending aorta is mostly hypothetical at this point. However, such repairs are being done with an increasing frequency. We have performed the technique in a small number of patients that will be the subject of a future publication, as we believe that the typical baseline anatomy of such patients must be defined before the applicability of "case reports" can be extrapolated to the general population.

Further limitations of this analysis relate to additional selection bias imposed on the work-up of dissection patients. At our institution, we maintain an evaluation protocol that is specifically tailored to the patient's presentation. Some patients are evaluated with high-resolution CT analysis, particularly when open surgical options are suboptimal, but CT scanning is not routinely done on every patient. Thus, detailed morphologic analyses are biased not only by the potential to undergo CT evaluation but also by the ability to administer contrast and obtain a study that has optimal temporal resolution.

CONCLUSIONS

Detailed anatomic information regarding the aortic root and ascending aorta are vital for consideration of endoluminal repair methods. Continued advances in CT scanning using high spatial and temporal resolution protocols with well-timed contrast boluses should provide adequate information to assess the presence of a flap, location of primary fenestrations, root involvement, and assess the relationship to critical root structures. Device development must consider the required length and diameter of the proximal sealing zone, the potential for detrimental effects of the device and delivery system on the aortic valve or coronary arteries, and the ability to be deployed accurately along both the greater and lesser curvature, in addition to accurate distal deployment at the level of the innominate artery. The effect of prior cardiac surgical procedures on the pathophysiology and morphology of proximal dissections requires further analysis. On the basis of our analysis, however, approximately one-third of patients in whom we had a preoperative CT scan were suitable for an endovascular stent graft repair.

AUTHOR CONTRIBUTIONS

Conception and design: MM, RG, JM
Analysis and interpretation: MM, RG, JM, ZM, QL, JD
Data collection: MM, RG, JM, ZM QL, JD
Writing the article: MM, RG
Critical revision of the article: MM, RG, ZM
Final approval of the article: MM, RG
Statistical analysis: AH
Obtained funding: RG
Overall responsibility: RG

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