Assessment of geometrical remodelling of the aortic arch after hybrid treatment

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Abstract

OBJECTIVES: The aim of this study was to measure the morphological remodelling of the ascending aorta, aortic arch and thoracic aorta after aortic arch hybrid treatment including debranching and stent graft implantation.

METHODS: Preoperative, 1-month and 1-year follow-up of computed tomography angiography scans of 22 patients were analysed to compute the lumen centreline from the aortic root to the coeliac trunk, and the following measurements were derived: the total centreline length, distance from the aortic root to the left subclavian artery, distance from the left subclavian artery to the distal landing zone. For both pre- and postoperative centrelines, the pointwise curvature was measured at the proximal and the distal landing zones. The mean

†The first two authors contributed equally to this paper.
curvature values of the whole aortic segment and the endografting region of the ascending and the descending aorta were measured. Surface outerline was computed as well, and curvature values at the endograft landing points were extracted.

RESULTS: At the 1-month follow-up, centreline length were already significantly increased (382.66 ± 48.69 to 388.1 ± 50.75 mm; P = 0.01). Centreline pointwise curvature increased in the proximal (+29%, P = 0.011) and the distal zones (+63%, P = 0.004). Similarly, pointwise curvature of the outerline significantly increased in the proximal (+77%, P = 0.01) and the distal landing zones (+100%, P = 0.04). The centreline mean curvature increased in the ascending aorta (+7%, P = 0.02) and decreased in the endografting region (-3.3%, P = 0.004). No evidence of a relationship of such a remodelling with the type of endograft and the type of pathology was observed. This remodelling trend was confirmed by the analysis of 1-year computed tomography angiographies.

CONCLUSIONS: Hybrid arch repair was associated with a significant elongation of the vessel and a significant increase in the curvature on the ascending aorta and the descending aorta and on the endograft proximal and the distal landing zones.

Keywords: Aortic diseases • Aortic arch • Hybrid procedure • Geometric analysis

INTRODUCTION

Although recent guidelines recommend the endovascular approach as the treatment of choice for patients affected by thoracic aortic diseases [1], the anatomy of the thoracic aorta may affect the feasibility of this approach in many settings. In particular, the need to obtain an adequate proximal landing zone of the healthy aorta is crucial to avoid proximal type I endoleak or endograft migration [2]. Indeed, proximal landing zones with an at least 20 mm-long, healthy and relatively straight neck are needed for thoracic endograft placement [3].

On the contrary, in patients with short and highly angulated landing zones, a hybrid arch treatment performed in Ishimaru’s zones 0, 1 or 2 [4] has been introduced as a feasible technique for revascularization of the supra-aortic vessels to obtain an adequate proximal landing zone for thoracic endovascular aortic repair (TEVAR).

Unfortunately, the aortic arch is a critical zone for device delivery, and its intrinsic shape plays a crucial role in the rate of acute failure of thoracic endografts [5]. Indeed, the deployment of an endograft inside the flexible aortic tissue might lead to hard-to-predict morphological variations of the vessel shape that can be correlated with short-, mid- and long-term complications. Identifying the changes in aortic arch morphology between pre- and postoperative configuration could, therefore, be important to understand the causes of such complications and to predict procedure-related adverse events.

To date, other investigators have already focused on the role of anatomical factors in positioning outcomes [6] or have evaluated the changes in the aortic arch curvature following TEVAR [7]. However, little is known about the geometric changes that occur at landing zones after aortic arch hybrid treatment and how these could be related to possible complications.

On the basis of these considerations, the aim of our study was to measure the morphological remodelling of the thoracic aorta in patients who underwent aortic arch hybrid treatment. Aortic remodelling was measured by a quantitative analysis of the aortic geometry before and after a hybrid arch repair.

MATERIALS AND METHODS

The research protocol was submitted to the local institutional medical ethics committee; the need for informed consent from the patients was waived because of the retrospective nature of the analysis and the use of anonymous data.

Patient selection

A single-centre, retrospective study was conducted on all consecutive patients who underwent aortic arch hybrid treatment between January 2012 and December 2016.

Only patients treated in zones 0, 1 or 2 according to the Ishimaru classification [4] were included in the study, whereas patients who did not undergo supra-aortic vessels revascularization or those with previous open repair of the ascending aorta (AsAo) were excluded; type B aortic dissections (n = 3) were excluded as well due to the great remodelling of the true lumen after TEVAR.

On the basis of such criteria, a total of 22 cases were included: the mean age of the patients was 70.4 years (range 31–89 years), and 15 subjects were men. Nine patients presented with thoracic aortic aneurysms, 9 had penetrating aortic ulcer complicated by a pseudoaneurysm and 4 had an aortic intramural haematoma. Proximal landing zones 0 (Z0), 1 (Z1) and 2 (Z2) were involved in 10, 3 and 9 patients, respectively. Patient characteristics are listed in Table 1.

All procedures were performed under general anaesthesia: 9 were single-staged and 13 were 2-staged. In the 2-stage repair, the first stage consisted of supra-aortic vessels revascularization, and the second stage was the endovascular endograft deployment. The median time interval between the 2 procedures was 21 days; the median time interval between preoperative and 1-month computed tomography angiography (CTA) and between preoperative and 1-year CTA was 40 and 378 days, respectively.

Patients with landing zone 0 underwent debranching of the supra-aortic vessels (Fig. 1). This surgical procedure was carried

<table>
<thead>
<tr>
<th>Table 1: Patient data and comorbidities</th>
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<td>Total</td>
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<tr>
<td>n</td>
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<tr>
<td>Age (years), mean ± SD</td>
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<tr>
<td>Female, n (%)</td>
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<tr>
<td>Hypertension, n</td>
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<td>Diabetes, n</td>
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<td>Chronic obstructive pulmonary disease, n</td>
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<td>Coronary heart disease, n</td>
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<td>Atrial fibrillation, n</td>
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<td>Chronic renal failure, n</td>
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SD: standard deviation.
out by means of an end-to-side anastomosis between the partially clamped AsAo and the brachiocephalic trunk and the left common carotid artery using a bifurcated polyester textile graft. The left subclavian artery was revascularized during TEVAR by carotid–subclavian artery bypass.

Patients with landing zone 1 underwent right common carotid artery to left subclavian artery bypass (using an 8–10-mm diameter stretch polyester textile graft), whereas the left common carotid artery was reimplanted on bypass with an end-to-side anastomosis (Fig. 1).

Patients with a landing zone 2 underwent carotid-subclavian artery bypass. Debranching was carried out by means of an end-to-side anastomosis between the left common carotid artery and the left subclavian artery using an 8–10-mm diameter stretch polyester textile graft (Fig. 1).

The technical success was defined by an accurate endograft deployment without the need for an additional endograft deployment and the coverage of target-selected aortic vessels.

**Imaging analysis protocol**

All 22 patients underwent preoperative and 1-month postoperative contrast-enhanced CTA, while 19 of them were considered for 1-year follow-up analysis; indeed, 3 patients did not undergo 1-year postoperative CTA due to death in 1 case and reintervention in 2 cases before the completion of 1-year follow-up. The slice thickness and the pixel spacing were in the range of 0.5–1.25 mm and 0.55–0.97 mm, respectively. All scans were transferred to a workstation in an anonymous format for image processing as described below. The whole processing procedure was performed using the open-source Vascular Modelling Toolkit library [8]. An overview of the image processing workflow is shown in Fig. 2. Firstly, we performed a semiautomatic gradient-based level set segmentation to extract a 3-dimensional (3D) model of the thoracic aorta lumen. Segmentation of postoperative images could also be used to retrieve the endografts 3D models. Afterwards, each postoperative vessel surface was
automatically registered to the preoperative one by means of the Iterative Closest Point algorithm [9], a robust method for a rigid registration of 3D data, which is implemented in the Vascular Modelling Toolkit as well. Finally, pre- and postoperative centre-lines were automatically computed [10] from the sinotubular junction of the aortic root (AR) to the plane crossing the coeliac trunk.

When the preoperative 3D geometries involved saccular aneurysms, a virtual preoperative surface model excluding the aneurysmal sac was created. This procedure was performed to prevent the vessel centreline from being affected by the bulbous protrusion. The removal of the saccular aneurysm was performed by identifying the centreline points that define the area of influence of the sac, removing the portion of centreline among these extremities and finally creating a new interpolated parent artery centreline. The original method already implemented in the Vascular Modelling Toolkit was partially modified to manually adjust the position of the 2 points delimiting the aneurysmal sac.

Given the lumen centreline, we performed the following measurements: length of the whole centreline (L); length of the centreline covered by the endograft(s) (CL); distance from the AR to the proximal edge of the left subclavian artery (D_{AR-LSA}); distance from the left subclavian artery proximal edge to the distal landing zone (D_{LSA-D}). CL was automatically computed by projecting the 3D model of the endograft(s) into the postoperative aortic lumen centreline. All these measurements are illustrated in Fig. 3A.

Curvature was quantified along the extracted paths (the centreline and the outerline) for all patients. At a given point, curvature is defined as the inverse of the radius of the local osculating circle, i.e. the circle approximating the curve at a given point. On the basis of this definition, the value of curvature at a certain point quantifies its deviation from a straight line as illustrated in Fig. 3C.

As preoperative and postoperative vessel surfaces were automatically registered with the Iterative Closest Point algorithm, the position of the endograft was also identified onto the preoperative path lines, thus allowing us to measure the local curvature values on both pre- and postoperative paths (centreline and outerline) in 2 specific points: the proximal (P1) and the distal (D1) extremities of the aortic portion involved in the endovascular implant(s). The position of these points is highlighted in Fig. 3B.

Furthermore, the values of local curvature computed along the centreline were averaged to obtain the preoperative and postoperative mean curvatures of the total aorta (from the AR to the coeliac trunk), the AsAo (from the AR to P1), the endografting region (ER) (from P1 to D1) and the descending aorta (from D1 to the coeliac trunk).

Calculations were made both for the whole group of patients (n = 22) and for the 2 sub-groups, i.e. Z0 (n = 10) and Z1–2 (n = 12). Patients with landing zones Z1 and Z2 were grouped together (Z1–2) due to the limited number of Z1 cases (n = 3) and similar aortic arch morphology between Z1 and Z2. As mentioned before, at 1-year, 3 patients were lost to follow-up (2 patients in the Z0 group and 1 patient in the Z1–2 group).

### Statistical analysis

All statistical analyses were performed using the JMP 13.0 (SAS Institute Inc. Cary, NC, USA) software.

Data are shown as absolute frequencies, percentages, median with a range and mean ± standard deviation, where appropriate. The Shapiro–Wilk’s test and the visual investigation of data with histograms were used to assess the normal distribution of the data. All significant differences between pre- and postoperative geometric measurements were analysed by means of the Paired-samples t-test. Comparisons between different groups of devices and the various pathologies were performed individually using the one-way analysis of variance for unequal sample...
sizes. Univariate correlations were examined using the Pearson’s correlation coefficient. P-values <0.05 were considered statistically significant in all statistical tests. No correction for multiple testing was performed, thus all significant values should be interpreted with caution.

Although the pipeline we proposed allowed us to minimize the users’ interaction, the semiautomatic segmentation phase of the vessel could potentially lead to slight measurement differences. Therefore, to validate the obtained results, 2 independent, skilled observers performed segmentation of CTA images and subsequent centreline extraction and measurements, and one of them conducted it twice, allowing for interobserver and intraobserver variability analysis using the intraclass correlation coefficient (ICC). The results were presented with the 95% confidence interval (CI).

RESULTS

Study subjects

Altogether, 41 endografts corresponding to 3 different types of devices were deployed for 22 procedures: 10 patients (45%) received the Low-Profile Zenith Alpha endograft (Cook, Bloomington, IN, USA), 7 (32%) received the Relay NBS endograft (Bolton, Barcelona, Spain) and 5 (23%) the Gore C-TAG endograft (W.L. Gore and Associates, Flagstaff, AZ, USA).

Technical success was achieved in 100% of cases. No intraoperative deaths, paraplegia or other major complications occurred. The following complications were observed during follow-up: 1 case of type Ib endoleak at 1-month follow-up, 1 case of asymptomatic retrograde type A aortic dissection (rTAAD) revealed by 1-month CTA which required reintervention, 1 case of aortic dissection on the distal landing zone at 3-month follow-up resolved by open repair and 1 case of pseudoaneurysm with aortic rupture on the distal landing zone at 1 year of follow-up with required endovascular reintervention. Two deaths occurred within the 1-year follow-up due to complications after reintervention. Of these 2 patients, 1 died from sepsis after open repair for rTAAD and another patient died 2 months after reintervention for aortic rupture.

Analysis of geometrical remodelling

One-month results. The values of computed geometrical quantities regarding both pre- and postoperative aortic centrelines are reported in Table 2 (the total group of patients), Table 3 (the Z0 group) and Table 4 (the Z1–2 group). The percentage of the endograft coverage CL was 60 ±17 and 1.8 ± 0.7 endografts were used per patient. Although not statistically significant, longer segments of the aorta were stented in subjects in the Z0 group compared to those in the Z1–2 group (65 ±20% vs 56 ±15%, P = 0.1).

After hybrid repair, the centreline length significantly increased (P = 0.01) for the whole group of patients, albeit to a rather small degree, i.e. 1.35%. Such a change in length was statistically significant in the Z0 group (P = 0.04) alone, showing an average increase of 2.3%; conversely, the Z1–2 group did not show centreline lengthening (P = 0.1).

The degree of pointwise curvature at the endograft landing points was assessed numerically (Fig. 4). Just 1 month after treatment, centreline local curvature was significantly greater in both P1 (P = 0.011) and D1 (P = 0.004). Considering the Z0 group, the increase in curvature in P1 was detected even if no statistical significance was reached (P = 0.06), whereas centreline local curvature significantly increased (P = 0.04) in the distal landing zone D1. With regard to the Z1–2 group, a significant increase in the curvature was found in both the P1 (P = 0.03) and the D1 (P = 0.02) zones.

Similarly, the pointwise curvature of the surface outerline (Fig. 4) significantly increased in P1 (P = 0.01) and D1 (P = 0.04) for the total group of patients. No statistical significance was reached for the Z0 group even if an increase of approximately 40% of curvature values was detected in P1 (P = 0.055), whereas a significant increase was observed on both P1 (P = 0.01) and D1 (P = 0.03) when the Z1–2 group was considered.

Following hybrid repair, the centreline mean curvature showed a significant increase (+7%) in the ASS (P = 0.02) and a significant decrease (-3.3%) in the ER (P = 0.004). Regarding the mean curvature values in group Z0, a statistically significant increase (+14.5%) in the mean curvature was observed in the ASS (P = 0.008) together with a decrease (-3%) in the mean curvature in the ER (P = 0.05). For group Z1–2, a significant reduction

Table 2: Measurements for the whole group of patients

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Preoperative</th>
<th>1-Month follow-up</th>
<th>1-Year follow-up</th>
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<tbody>
<tr>
<td>L (mm), mean ± SD</td>
<td>382.7 ± 48.7</td>
<td>388.1 ± 50.7, P = 0.010</td>
<td>395.1 ± 47.7, P = 0.001</td>
</tr>
<tr>
<td>D_{ASA,LSA} (mm), mean ± SD</td>
<td>114.1 ± 18.7</td>
<td>117 ± 19.3, P = 0.02</td>
<td>119.7 ± 17.9, P &lt; 0.001</td>
</tr>
<tr>
<td>D_{LSA,D} (mm), mean ± SD</td>
<td>190.51 ± 79.90</td>
<td>192.51 ± 74.64</td>
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</tr>
<tr>
<td>Centreline curvature × 10 (1/mm), mean ± SD</td>
<td></td>
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</tr>
<tr>
<td>P1</td>
<td>0.22 ± 0.08</td>
<td>0.27 ± 0.16, P = 0.011</td>
<td>0.4 ± 0.2, P &lt; 0.001</td>
</tr>
<tr>
<td>D1</td>
<td>0.09 ± 0.063</td>
<td>0.15 ± 0.12, P = 0.004</td>
<td>0.23 ± 0.13, P &lt; 0.001</td>
</tr>
<tr>
<td>TA</td>
<td>0.18 ± 0.02</td>
<td>0.18 ± 0.02, P = 0.12</td>
<td>0.21 ± 0.04, P = 0.04</td>
</tr>
<tr>
<td>AsAo</td>
<td>0.19 ± 0.04</td>
<td>0.21 ± 0.04, P = 0.02</td>
<td>0.24 ± 0.08, P = 0.05</td>
</tr>
<tr>
<td>ER</td>
<td>0.20 ± 0.04</td>
<td>0.19 ± 0.03, P = 0.004</td>
<td>0.20 ± 0.04, P = 0.06</td>
</tr>
<tr>
<td>DsAo</td>
<td>0.11 ± 0.05</td>
<td>0.12 ± 0.07, P = 0.090</td>
<td>0.18 ± 0.07, P = 0.02</td>
</tr>
<tr>
<td>Outerline curvature × 10 (1/mm), mean ± SD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>0.32 ± 0.23</td>
<td>0.49 ± 0.37, P = 0.01</td>
<td>0.5 ± 0.18, P = 0.04</td>
</tr>
<tr>
<td>D1</td>
<td>0.11 ± 0.06</td>
<td>0.18 ± 0.09, P = 0.04</td>
<td>0.41 ± 0.04, P = 0.04</td>
</tr>
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</table>

ASAo: ascending aorta; D_{ASA,LSA}: distance from the AR to the proximal edge of the left subclavian artery; D1: distal; D_{LSA,D}: distance from the left subclavian artery proximal edge to the distal landing zone; DsAo: descending aorta; ER: endografting region; P1: proximal; SD: standard deviation; TA: total aorta.
One-month follow-up; the same applies with the mean curvature. Distal landing zones confirm the increase already observed at 1-year follow-up, values of pointwise curvature at proximal and observed when compared to preoperative configuration. At 1-month follow-up, values of pointwise curvature at proximal and observed when compared to preoperative configuration. At concerns the centreline length, a mean increase of +12.3 mm was confirmed the remodelling trend of the aorta. In particular, as curvature increase. was found between the centreline length increase and the mean age length CL and other computed quantities. No correlation statistically significant correlation was found between the cover- were found regarding the changes in the centreline lengths. No differences were detected for any of the computed parameters, groups. Subsequently, considering the pathology, no significant (-3.4%).

In particular, the high variability of the aortic arch anatomy [6, 11], which is further modified by the pathologies [12], leads to a significant increase in the unstented regions of both the ascending aorta and the descending aorta.

Intraobserver and interobserver reproducibility analyses

Intraobserver and interobserver reproducibility analyses were computed by the ICC. The intraobserver ICC index resulted in 0.98 (95% CI 0.97–1.00) for length measurements. An interobserver analysis showed an ICC index of 0.97 (95% CI 0.97–0.98) for length measurements. These results indicated an excellent intraobserver agreement and an interobserver agreement for length measurements.

**DISCUSSION**

The endovascular treatment of aortic diseases involving the thoracic area presents several anatomical challenges (i.e. a complex 3D anatomy and the presence of supra-aortic vessels). In particular, the high variability of the aortic arch anatomy [6, 11], which is further modified by the pathologies [12], leads to a
specific adaptation between the endograft and the aortic wall depending on each type of morphology.

Therefore, with the currently available thoracic endoprostheses, a total endovascular repair of the aortic arch requires devices that need to be customized for each patient’s anatomy and pathological condition, and often surgical left subclavian artery revascularization is required.

Thus, the hybrid procedure of the aortic arch, which includes supra-aortic vessels transposition to obtain an adequate proximal landing zone for TEVAR in zones 0, 1 and 2, has proved to be an effective alternative, especially in high-risk patients, in an effort to reduce perioperative death and complications related to open surgical repair [13]. However, the long-term outcomes of the hybrid treatment still remain a source of concern, and severe complications could occur during follow-up [14]. When passively bent inside a highly curved artery as the aortic arch, the endograft exerted a spring-back force at the proximal and distal ends due to the inherent tendency to recover its original straight status [15]. As already postulated, this spring-back force could cause an increase in stress on the outer wall, especially at the endograft landing zones, ultimately leading to endograft-related vessel injuries [16].
The aim of this study was to analyse the geometric changes of the aortic arch after the hybrid treatment, with particular focus on the endograft landing zones, attempting to enhance the understanding on the possible reasons for the development of device-related complications.

Our results indicated that a hybrid treatment modifies the morphology of the aortic arch tract, with both a significant elongation of the vessel and an increase in the pointwise and mean curvature.

In particular, with regard to the centreline length, a mean increase of 5.3 mm (P = 0.010) was already observed at 1 month after the treatment and it increased to +12.3 mm (P = 0.001) at 1-year follow-up; this result is consistent with the outcomes reported by Nauta et al. [17] and Naguib et al. [18].

After the hybrid treatment, the local curvature of the centreline was significantly greater in the endograft proximal landing zone compared to the preoperative configuration, which supports the findings by Midulla et al. [19]. Moreover, we also observe a significant increase in the centreline local curvature at the distal fixation zone, for which no comparative results can be found in the literature.

The significant increase in centreline curvature and outerline curvature at endograft landing points reveals the tendency of the endograft to spring back to its original straight status, as already documented by Kadoglou et al. [20].

In conclusion, we have demonstrated that the hybrid treatment is associated with a significant elongation of the vessel and a significant increase in curvature on the AsAo and on the endograft landing zones, which could be predictive of the development of device-related complications. This issue reveals the need for further investigation into more conformable and dedicated endografts, or even precurved endografts, for different thoracic aortic diseases.

CONCLUSION

In conclusion, we have demonstrated that the hybrid treatment is associated with a significant elongation of the vessel and a significant increase in curvature on the AsAo and on the endograft landing zones, which could be predictive of the development of device-related complications. This issue reveals the need for further investigation into more conformable and dedicated endografts, or even precurved endografts, for different thoracic aortic diseases.

Our results stress the importance of continued surveillance with CTA imaging for patients with this type of surgery to detect if any deformation or possible lesion at the impact point of the stent on the aorta outer wall will occur during follow-up.

Limitations

The main weakness of this study is the small number of enrolled patients, although the sample size is consistent with recent studies regarding quantitative assessment of aortic arch geometry [7]. Another limitation relates to the absence of a standardized protocol for the acquisition of CTA images, which is due to the retrospective design of the study. In addition, CTA acquisitions were not electrocardiogram (ECG) synchronized because this technique was not available at our centre for daily clinical practice. However, it is worth noting that even other studies, which are similar to the present one, did not make use of ECG-gated CTAs [7, 18, 19].

Conflict of interest: none declared.

REFERENCES


