Novel multi-dimensional modelling for surgical planning of acute aortic dissection type A based on computed tomography scan

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Abstract

OBJECTIVES: Acute type A aortic dissection (TAAD) is a life-threatening emergency and requires immediate surgical intervention. We propose a novel finite element multi-dimensional modelling (FE-MDM) technique to identify aortic tears preoperatively to aid surgical preplanning.

METHODS: Thirty-two patients with TAAD were included in this retrospective study. Computed tomography (CT) scans were imported using the segmentation software and reconstruction resulted in modelling of single TAAD components: aortic wall, false lumen, true lumen, gap in the flap and blood in both lumens. CT scans were processed by interpreters who were blinded to the clinical data and then compared with operative findings. The models were assessed and compared regarding localization and size of the entry tear with the intraoperative findings. Image set data were retrieved from CT scans.

RESULTS: Surgical inspection confirmed the localization of the tear obtained by the model in all patients with a 100% chance prediction (P < 0.0001) in all patients. With the simulation of the guided-cannulation, it was possible to place the cannula in the ascending aorta in 100% of patients (P < 0.0001 vs surgery). Using the virtual volume model, the chance of inserting into the false lumen was 0% (P < 0.0001). There was a strong correlation between the virtual volume model and cannulation in the true lumen (r = 0.88, P < 0.0001).

CONCLUSIONS: The FE-MDM technique of aortic dissection is helpful in identifying the site of the tear and may be considered as an additional tool in surgical preplanning. It may also enhance the efficiency of deep hypothermic circulatory arrest in patients with single entry sites in the ascending aorta and it may facilitate direct cannulation of the ascending aorta.

Keywords: Aortic dissection • 3D modelling • Quantification • Aortic tear

INTRODUCTION

The recognition of aortic valve repair is a well-established alternative to standard aortic valve replacement [1, 2], and the widespread use of transcatheter aortic valve replacement has refocused the need for high-quality quantitative imaging of the aortic apparatus leading to the development of three-dimensional (3D) modelling of the aortic valve and aortic root [3–6]. Type A aortic dissection (TAAD) is a life-threatening clinical emergency that continues to pose a significant challenge for clinicians. Numerical simulations have been widely used for the prediction of disease progression and therapeutic outcomes, by providing detailed insights into the haemodynamics [7]. However, for accurate pretreatment planning, the reliable identification of the true and false lumen is crucial. Nonetheless, a reliable and widely accepted system capable of displaying the different lumens in an easy and comprehensive way is not yet available. In addition, precise prediction of the localization of the entry tear and exclusion of additional entry tears further downstream may be very helpful towards a planned full arch replacement or even elephant trunk procedure instead of a quick decision when the arch is inspected in circulatory arrest.

An important issue in surgical preplanning of TAAD is the arterial cannulation to establish cardiopulmonary bypass and to allow a more physiological perfusion, in which the current cannulation techniques include retrograde cannulation through the femoral artery and antegrade cannulation through the axillary, brachiocephalic artery and in limited cases through direct cannulation of the ascending aorta. Therefore, reliable preoperative identification of an ascending aortic tear and analysis of the thickness of the aortic wall may help to guide direct aortic cannulation, permitting a more physiological antegrade perfusion through the ascending aorta and avoiding disadvantages of other cannulation options.

In this study, we present a novel finite element multi-dimensional modelling (FE-MDM) as a new method to identify the two TAAD lumens as well as to retrieve the intimal flap and the site of single or multiple intimal tears for accurate surgical preplanning.
The reliability of the model was also assessed comparing the localization of the entry tear with the intraoperative findings.

MATERIALS AND METHODS

Patient population

The patient population consisted of 32 consecutive subjects with Type A aortic dissection undergoing surgery at Maastricht University Hospital (MUMC, Maastricht, Netherlands). Patient characteristics are summarized in Table 1. All patients underwent computed tomography (CT) scans, which were retrospectively processed and compared with operative findings. Surgery was routinely performed. Surgical details are given in Table 2.

Cardiac computed tomography imaging

Cardiac computed tomography (CT) imaging was done using a 64-slice multi-detector CT scanner (Siemens Medical Solutions USA, Inc., Malvern, PA, USA) with 0.6 mm collimation, 100–120 kVp, 500–900 mAs and retrospective ECG gating with dose modulation. Contrast (Ultravist 300, Bayer) was injected through a peripheral intravenous catheter (20-gauge) followed by a saline bolus (40–60 ml) at 4 ml/s during an acquisition with inspiratory breath-hold. Scans were reconstructed for multiple cardiac phases with a slice thickness of 0.6 mm yielding an isotropic spatial resolution.

Finite element multi-dimensional modelling

The patient’s CT dataset (Fig. 1) was imported into an open source image processing and visualization software (3D Slicer 3.3.6, Kitware, Inc., New York, NY, USA), in which extraction of the aortic dissection components (true and false lumen, tear, blood and aortic wall; Fig. 2A–C) was automatically completed in separate steps and different colours; these were then reunited in one model (Fig. 2). First, the intrathoracic structures were rendered automatically, creating a surface model (Fig. 1D and E). These were thresholded automatically to create robust solid models [8]. The lower intensity threshold was defined as 200 Hounsfield units (HU) and the upper intensity threshold was defined as 600 HU. The models were cleaned by eliminating leaked voxels from the region-growing algorithm to preserve the originality of the model components. Final manual segmentation corrections were performed to eliminate irrelevant artefacts. The 3D-segmented model was imported by the open source meshing software (Meshlab 1.3) to mesh the model volumetrically in a tetrahedral way and to enable recognizing and differentiating between dissection components (true and false lumen, tear, blood and aortic wall; Figs 2 and 3A). The preoperative model demonstrates the exact anatomy of the aorta, including valve, coronary arteries, ascending aorta, aortic arch and descending aorta. The time for the whole model processing takes 10–15 min.

Virtual cannulation of the aorta

The virtual aortic cannula was designed by using open source CAD software (Free CAD) with diameters equivalent to the regular cannula used in classic aortic cannulation (6.5 mm). The aorta was cannulated in all patients by a skilled cardiac surgeon, not involved in the study and blinded to its main purpose, in two ways: (i) surface rendered model and (ii) volumetric model. The operator inserted the virtual aortic cannula in the regular place of the distal part of the ascending aorta. The virtual aortic cannula was inserted in two directions, medially and laterally (Fig. 4).

Measuring of three-dimensional geometric variables

The models were analysed in two steps: (i) step-by-step visual inspections of the models from different angles; (ii) direct measurements of different distances and angles. The analysis was performed in a sequential manner, first identifying the site of aortic tears (Fig. 5) and then measuring the dimension of the aortic tears.

Statistical analysis

Numerical data are displayed as mean and standard deviation, whereas binary data are expressed as percentage. Pearson’s $\chi^2$ test

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**Table 1:** Patient characteristics ($N = 32$)

<table>
<thead>
<tr>
<th>Gender</th>
<th>Male 18 (56.3)</th>
<th>Female 14 (43.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>65.1 ± 11.1 (range: 38–79)</td>
<td></td>
</tr>
<tr>
<td>Hypertension</td>
<td>29 (90.6)</td>
<td>7 (21.9)</td>
</tr>
<tr>
<td>Penetrating ulcer</td>
<td>1 (3.1)</td>
<td>0 (0.0)</td>
</tr>
<tr>
<td>LVEF &gt;45%</td>
<td>30 (93.7)</td>
<td></td>
</tr>
<tr>
<td>Myocardial infarction</td>
<td>2 (6.3)</td>
<td></td>
</tr>
<tr>
<td>Pericardial effusion</td>
<td>6 (18.8)</td>
<td></td>
</tr>
<tr>
<td>Aortic valve regurgitation</td>
<td>5 (15.6)</td>
<td></td>
</tr>
<tr>
<td>PVD</td>
<td>1 (3.1)</td>
<td></td>
</tr>
<tr>
<td>Reoperations</td>
<td>2 (6.3)</td>
<td></td>
</tr>
</tbody>
</table>

Values are shown as mean ± standard deviation or number (percentage) for categorical data.

LVEF: left ventricular ejection fraction; PVD: peripheral vascular disease.

**Table 2:** Surgical data ($N = 32$)

| Surgical procedure | SAAR 5 (15.6) | SAAR + root reduction 1 (3.1) | SAAR + AVP 1 (3.1) | SAAR + arch 5 (15.6) | SAAR hemi-arch 11 (34.4) | SAAR hemi-arch + AVP 1 (3.1) | IAAR 5 (15.6) | IAAR hemi-arch 2 (6.2) | David operation 1 (3.1) | DHCA time (min) 54.1 ± 34.3 | DHCA temperature (°C) 24.2 ± 1.4 | Cerebral perfusion time (min) 282 ± 99.1 | Cross-clamp time 123.4 ± 64.2 |

Values are shown as mean ± standard deviation or number (percentage) for categorical data.

was employed to compare proportions. Linear correlation was used to describe the relationship between cannulation in the true lumen as a dependent variable and the virtual model as an independent variable. Statistical analysis was performed using IBM SPSS Statistics Version 20 (IBM Deutschland GmbH, Ehningen, Germany). A probability value of <0.05 was considered statistically significant.

RESULTS

Our model showed that the intimal tear was localized in the ascending aorta in 29 patients (90.6%): in 17 it was isolated in the ascending aorta (53.2%), in 1 (3.1%) it was multiple in the same position, and in 11 (34.3%) it was localized in the first portion of the aorta and in the aortic arch. In only 3 (9.4%) patients, the tear was isolated in the ascending arch. Surgical inspection confirmed in all patients the localization of the tear obtained by the model with a 100% chance prediction ($P < 0.0001$). Aortic cannulation was employed in only 2 cases (6.2%) and in 1 of these, a second cannula was placed in the femoral artery. The other sites of cannulation were: the left femoral artery in 7 (21.8%), right femoral artery in 19 (65.5%), right and left femoral arteries in 1 (3.1%) and left subclavian artery in 3 (9.4%). With the simulation of guided-cannulation, it was possible to place the cannula in the ascending aorta in 100% of patients ($P < 0.0001$ vs surgery). With virtual cannulation, the chance of being in the aortic true lumen was 12.5%, whereas with the volume model, the chance of being in the false lumen was 0% ($P < 0.0001$). There was a strong correlation between the virtual volume model and the cannulation in the true lumen ($r = 0.88$, $P < 0.0001$), whereas this correlation was weak with the rendered virtual cannulation ($R = 0.08$, $P > 0.9$).

Figure 1: Three-dimensional (3D) reconstruction of the aortic dissection components. (A) Computed tomography scan of the chest showing the dissected aortic arch. (B and C) 3D surface rendering of the aorta and surrounding structures. (D–F) Processing of the images by segmentation of the aorta and the flap which divided the aorta into the false and the true lumen.

Figure 2: Three-dimensional (3D) segmentation of the aortic dissection. (A and B) 3D rendering and modelling of the whole aorta. (C) 3D reconstruction of the flap and the tear which is circular in this case. (D) The components of the aortic dissection where the flap is dividing the aorta into the false and the true lumen, and the tear is coloured in blue, which is localized in the ascending arch. Also, the tear was measured internally and this measurement was visible from the external view.
Numerous methods have been used to diagnose aortic dissection in order to devise the best treatment strategies for the patients involved. These comprise CT (61%), transoesophageal echocardiography (33%), aortography (4%) and magnetic resonance imaging (2%) [9, 10]. However, advanced models may enhance a deeper understanding of the mechanistic aspects of TAAD and help clinicians to preplan surgery more accurately. Image segmentation is an important part of image processing. Several algorithms have been proposed for the automatic detection of the aorta [11–14]. Nonetheless, to the best of our knowledge, there are only a few published papers on aortic dissection segmentation [15–17] and there is no description of the real-world surgical application of such methods in daily clinical practice. Segmentation of a dissected aorta is challenging because of possible reconstruction errors due to disturbing artefacts in the image data, e.g. the inhomogeneous density of the contrast agent caused by flow.
variations in the lumens and reconstruction errors due to high contrast agent density. In addition, starting from CT images, the 3D view of the lumens is obtained either with difficulty by volume rendering or other visualization tools (which only directly gives the outer contour of the aorta) or by other segmentation methods since they mainly directly segment either the outer contour of the aorta or both other connected arteries and organs [18]. One of the so-called deformable models, the fast marching method, modified to separately segment the two lumens of the images, was employed for the 3D segmentation of the dissected aorta [17].

Figure 4: Virtual cannulation of the aorta, in which the three-dimensional (3D) modelling enables the surgeon to cannulate directly into the aorta and guides him to the best place for cannulation and the best direction for the cannula. The blue cannula was inserted into the right place according to 3D internal and external visualization, whereas the yellow cannula was inserted into the false lumen due to a change in its direction of insertion.

Figure 5: Internal and external measurement of the tear area as well as interior inspection and navigation through the aorta preoperatively enable the surgeon to visualize the aorta from inside.
However, most of these methods are not able to deal with the dissection membrane (intimal flap) within the aortic lumen, or are based only on greyscale differences for automatic lumen distinction. In addition, these methods are not always accurate enough to clearly identify and determine the frequency, locations and sizes of aortic intimal tears, which are important data for planning surgical aortic root replacement.

We presented a new FE-MDM method to identify the two TAAD lumens as well as to retrieve the intimal flap and the site of single or multiple intimal tears for accurate presurgical treatment planning. We segmented separately all the single aortic dissection components: true lumen, false lumen, intimal flap, intimal tear, blood and aortic tissue, and this allowed distinguishing multiple components with different properties and to resolve the error for multiple parameters. Segmentation was followed by manual cleaning aimed at eliminating leaking voxels from the region-growing algorithm and preserving the originality of the model components. This step was followed by meshing the components of aortic dissection. Meshing allowed generation of a more accurate model that enables better visualization and navigation inside all TAAD components for accurate presurgical planning.

We identified the localization of the intimal tear or multiple tears in 32 patients, which was matched to operative results. The FE-MDM system was able to measure the size of the tears and to detect distal tears not easily recognizable by CT due to motion artefacts [19]. There was a 100% concordance between the localization of the tears with our model and surgical inspection. The accurate preoperative localization of tears, especially those localized in the distal ascending aorta or arch, is crucial for a correct surgical strategy. The frozen elephant trunk procedure is one of the new treatment options to treat type A dissections with an entry in the distal aortic arch. In real-world surgery, the operator has only a short period of hypothermic circulatory arrest to visually explore the dissected arch and to choose between an open distal anastomosis of the graft and the conjoined aortic wall layers, in the absence of an arch tear, or an arch replacement beyond the entry-bearing portion if an entry tear traverses the aortic arch [20].

A detailed and precise preoperative analysis to assess whether extensive tears are present beyond the junction of the transverse and descending aortic segments, as well as characterization of distal perfusion and the size of both true and false lumens, is the cornerstone in the preoperative assessment of TAAD to plan a total arch replacement with reconnection of some or all supra-aortic vessels to the graft during deep hypothermic circulatory arrest (DHCA) and retrograde or antegrade head perfusion or perfusion via the brachiocephalic artery [21].

Furthermore, whereas in our real-world surgery the aorta was cannulated only in 3.2% of patients, our FE-MDM reconstruction would have allowed an aortic cannulation in all subjects with 100% perfusion of the true lumen by the cannula. Therefore, reliable preoperative identification of an ascending aortic tear and analysis of the thickness of the aortic wall may help to guide direct aortic cannulation. Allowing a more physiological antegrade perfusion through the ascending aorta may improve efficient usage of DHCA in patients with a sole entry site in the ascending aorta.

Indeed, the absolute necessity for DHCA once cerebral physiology is provided has been questioned. In addition, concerns have also grown among surgeons about the effectiveness of mild-to-moderate hypothermia for protecting visceral organs and the lower body during circulatory arrest, especially when a long arch repair time is required [22,23].

Finally, an accurate 3D reconstruction of the dissected aorta may help to avoid distal malperfusion with lower limb ischaemia, gut ischaemia or renal failure and stroke, which significantly increase mortality [24].

As we have described this FE-MDM technique in a previous mitral valve study [25], this technique segments aortic dissection components in an automatic way. There remains a requirement for user interaction in automatic separation of these components. This processing requires ~10–15 min of an expert’s time, which will not limit the clinical applicability of the FE-MDM technique. The FE-MDM technique is designed and developed with the help of free access softwares, which enable better acquisition and reducing the processing costs.

**CONCLUSIONS**

FE-MDM reconstruction of aortic dissection is helpful in identifying the site of the tear and may be considered as an additional tool in surgical preplanning. It may also enhance the efficient usage of DHCA in patients with single entry sites in the ascending aorta and it may facilitate direct cannulation of the ascending aorta.

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**Conflict of interest:** All authors had full control of the study design, methods used, outcome parameters, analysis of the data and production of the written report. The models were designed and developed by Abdullrazak Hossien at Maastricht University Medical Centre.

**REFERENCES**


