Improved Assessment and Treatment of Abdominal Aortic Aneurysms: The Use of 3D Reconstructions as a Surgical Guidance Tool in Endovascular Repair

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ABSTRACT

Background: Endovascular repair is fast becoming the treatment of choice for abdominal aortic aneurysms in anatomically suitable patients. Precise sizing of the stent-graft ensures correct fixation of the stent and therefore helps to increase the life-span of the device. 3D reconstructions also allow further analyses of the problem using additional software to indicate possible rupture sites and unnatural flow patterns.

Methods: CT scan data for four male patients awaiting endovascular repair were obtained. Thresholding and segmentation of images is performed based on pixel intensities allowing 3D reconstruction. Wall stress was determined on one particular case using finite element analysis.

Results: 3D reconstruction allows measurement to be obtained than can be difficult to measure using 2D images, thus complimenting traditional 2D measurements, allowing the correct sizing of stent-grafts for each patient. Reconstructions also provided imaging of potential anatomical problems, for example, extreme tortuosity of the proximal neck and access vessel calcification. Wall stress results showed key regions that may be possible rupture sites.

Conclusion: 3D reconstructions greatly aid surgical planning. As stent-graft devices evolve, anatomical difficulties previously considered contraindications to endovascular repair can now be overcome with careful planning. 3D reconstruction is a useful adjunct to assessment and planning of endovascular repair.

Key Words: Abdominal aortic aneurysm, 3D reconstruction, endovascular repair, surgical planning.

Introduction

An abdominal aortic aneurysm (AAA) can be defined as a permanent and irreversible localised dilatation of the aorta [1]. Aneurysms form due to alterations of the connective tissue in the aortic wall. This degradation of the aortic wall is attributed to risk factors such as tobacco smoking, sex, age, hypertension, chronic obstructive pulmonary disease, hyperlipidaemia, and family history of the disorder [1]. With recent advancements in non-invasive diagnostic imaging more AAAs are being detected. Approximately 150,000 new cases are diagnosed each year in the US [2-4], and 15,000 deaths per year are attributed to AAA rupture [5]. The normal diameter of the abdominal aorta can vary with increasing age, male sex and bodyweight [1,2], and decreases progressively from its entry into the abdominal cavity to the iliac bifurcation. The infrarenal abdominal aortic diameter ranges from 15mm to 24mm for most elderly men [1] and it was proposed [6] that an abdominal aortic aneurysm is an aorta with an infrarenal diameter greater than 30mm. As the diameter of the infrarenal aorta is dependent on age and sex [7], a size of at least 1.5 times greater than the expected normal diameter of the infrarenal aorta [8], has been suggested as an appropriate definition of an aneurysm.

Currently, the indication for surgical intervention is based on the maximum diameter of the abdominal aortic aneurysm in the context of the patient's general health status, with most repairs performed when the aneurysm exceeds 50 to 60mm [9-12]. The aim of AAA treatment is to totally exclude the aneurysm, isolating the aneurysm sac from systemic blood pressure and flow so as to minimise the risk of rupture. As a result of AAA treatment, most aneurysms should stabilise or shrink [13], although, it has been reported that aneurysms can often enlarge after AAA treatment due to endotension [14]. Surgical repair can be either traditional open repair or endovascular repair (EVAR). With traditional surgical repair, the abdomen is entered via a long midline or a wide transverse incision. Clamping of the infrarenal, or rarely the suprarenal, aorta is necessary while suturing either a Dacron or expanded polytetrafluoroethylene (ePTFE) graft to the neck of the aorta proximal to the aneurysm and either the distal aorta (tube graft) or to both iliac arteries (bifurcated graft) distal to the aneurysm which is effectively removed from the circulation. Endovascular repair consists of the placement of a bifurcated graft via an intraluminal introducer across the aneurysm and its fixation to the normal aortic and iliac walls with self-expanding stents at both ends [1]. This treatment involves the surgical exposure of the common femoral arteries where the endovascular graft can be inserted by an over-the-wire technique. The early benefit of the minimally invasive EVAR approach has been proven in several randomised trials in reducing the perioperative mortality compared with open repair [14-17]. It is thought that this benefit is a result of the avoidance of the large abdominal incision and consequent systemic inflammatory response, respiratory and wound complications as well as the avoidance of aortic clamping with resultant cardiovascular complications.

The conversion of computed tomography (CT) scans into 3D reconstructions of patient-specific regions is of great use to surgeons and is becoming widely used [18]. For many years regions of the human body have been reconstructed in order to give clinicians a further insight into the particular problem region or condition. The focus of this paper is on the use of 3D reconstruction of the human abdominal aorta in patients suffering from aneurysmal disease. Also included in this study is the methodology and results of a finite element analysis (FEA) of a particularly extreme case of aneurysmal disease. FEA is a commonly used engineering technique to determine stress distributions experienced in complex structures and is used widely in biomedical engineering applications. The use of FEA in assessing the propensity of an aneurysm to rupture is becoming more widespread among researchers [11,12,19-22], and helps provide a useful insight into the biomechanical behaviour of the aorta. Ultimately, these reconstructions provide the clinician with valuable data regarding dimensions, geometry, and possible problem areas that may arise during endovascular surgical repair.

Methods

3D Reconstructions

Computed tomography (CT) scan data was obtained from the Midwestern Regional Hospital, Limerick, and St. James's Hospital, Dublin, for 4 patients awaiting surgical repair of an AAA. All patients were male with a mean age of 77.5yrs (range 59-87yrs). CT scans were obtained using a Somotom Plus 4

(Siemens AG, D-91052 Erlangen, Germany). The mean pixel size of the CT scans was 0.675mm with all scans taken using a 3mm slice increment. The CT scans were imported into the commercially available software Mimics v12 (Materialise, Belguim) for reconstruction. The full reconstruction technique has been reported previously by our group [23]. Briefly, a thresholding technique is applied to each scan in the series. This process assigns a pixel intensity value measured in Hounsfield units (HU) to each pixel in the image. From this, the HU value can be controlled so that only the regions of interest are thresholded. Following this thresholding, segmentation of the image is possible. This assigns a certain colour to a certain region of interest, in this case the diseased aorta. By applying this algorithm to the series of CT scans, a complete 3D reconstruction can be generated. This process can be seen in Figure 1.

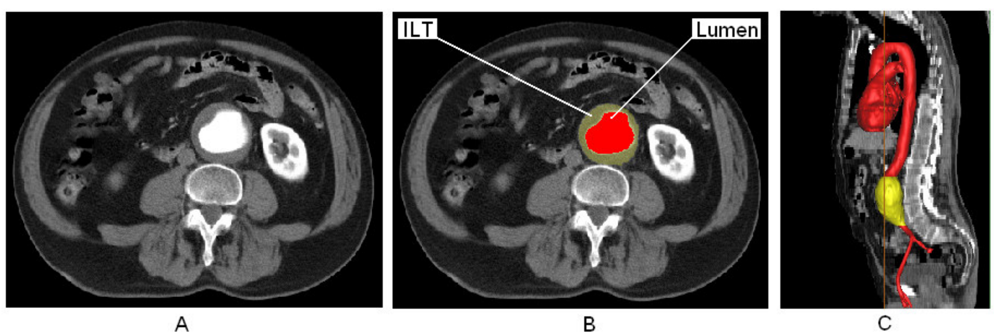

Figure 1: (A) Typical CT scan showing aneurysmal aorta in centre of image, (B) algorithm defines regions of interest and (C) software generates 3D reconstruction of desired regions.

Assigning regions into different layers allows certain areas to be highlighted or removed depending on the desired region of interest. An example of this layered approach to reconstruction can be seen in Figure 2. In this particular reconstruction, all major internal structures were generated for illustration purposes.

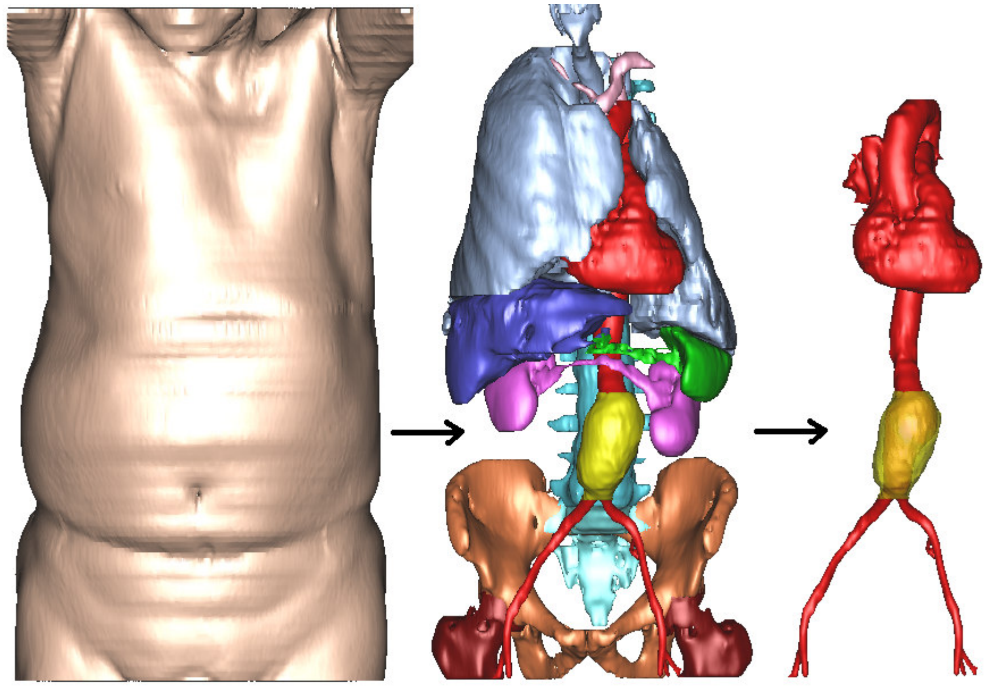

Figure 2: Full 3D reconstruction of CT scan data set. Image shows the use of layers to highlight/remove particular regions of interest depending on desired areas.

For these particular reconstructions, only the lumen regions were of clinical importance as this is the region to which the stent-graft is deployed and fixated. For the purposes of FEA, the full aneurysmal sac of the extremely diseased aorta was reconstructed.

Finite Element Analysis (FEA)

The process of determining wall stresses experienced within the aortic wall from CT scan data sets has been previously reported by this group [21,22,24]. The FEA technique works by subdividing the structure into smaller regions called elements, with each element connected via nodes. The resulting subdivision is known as a mesh. The stress at each node is then mathematically computed using the appropriate software, in this case ABAQUS v6.7 (Dassault Systemes, SIMULIA, R.I., USA). Realistic boundary conditions were then applied to the aorta. In this study, FEA was used to determine the resulting wall stress distributions for the extremely diseased case shown in Figure 3. The model was meshed using shell elements. The intraluminal thrombus (ILT) was omitted from the analysis. The ILT has been shown to reduce wall stress by acting like a mechanical buffer between the internal blood pressure and the aortic wall [24].

An internal peak systolic blood pressure of 120mmHg (16KPa) was applied to the internal region of the aorta, with the reconstruction constrained from movement at the entrance to the aortic arch and the iliac arteries to represent tethering to the remainder of the ascending aorta and the femoral arteries. The aortic wall was assumed to have a uniform thickness of 1.9mm [10,20,25], and was modeled as a non-linear hyperelastic material [10]. These boundary conditions have been implemented in many previous studies [10,19,21,22,24,26-28].

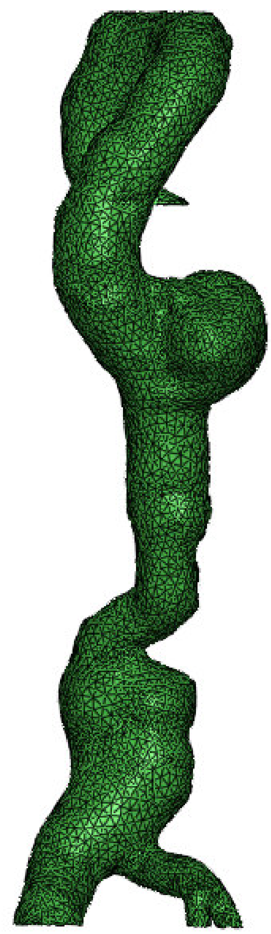

Figure 3: Meshed reconstruction for use in FEA. Case shown is that of an extremely diseased aorta with TAA, AAA and also IAA. Case shown here is from the posterior viewpoint.

Results

3D Reconstructions

Four patients awaiting surgical repair were reconstructed into virtual 3D models for examination. Reconstruction times can range from as little as 2 minutes for a basic model where minor details are ignored, to 1 hour where all details are included such as ILT and surface indentations. The critical dimensions when concerned with EVAR stent-grafts are the neck diameter of the stent-graft, the iliac diameter, and also the length of the device. Clinician's can usually determine the neck diameter without difficulty using 2D CT scans, but difficulties can arise when determining length. 3D reconstruction allows the overall length to be easily measured, thus allowing the exact sizing of the medical device. An example of this AAA length measurement can be seen in Figure 4. The measurements are taken from below the lowest renal artery to a point in the iliac arteries where the clinician fells comfortable will maintain an adequate fixation of the device.

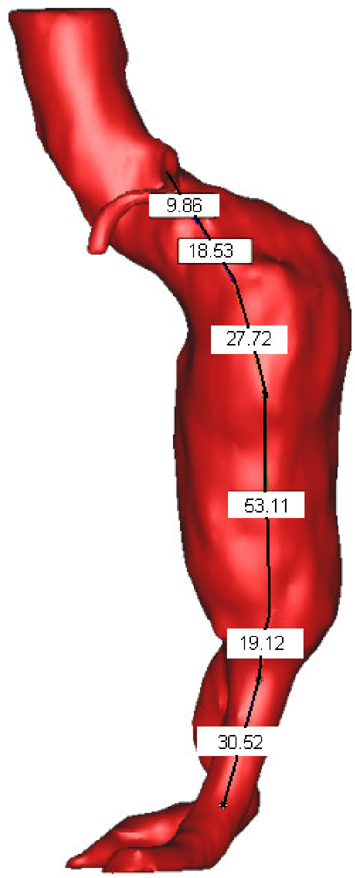

Figure 4: Example reconstruction showing measurements used to size stent-graft. All measurements are in millimeters (mm). Total length of stent-graft was determined to be 159mm.

Concerns arose about one particular patient when CT scans revealed an extremely tortuous proximal neck that may cause difficulties during the surgical procedure. 3D reconstruction highlighted the degree of curvature of the neck and allowed the clinician to decide on the most suitable approach before EVAR. As shown in Figure 5, the proximal neck of the AAA required special attention during the operation. As the upper portion of the stent-graft is embedded into the proximal neck, the tortuous nature of this could complicate placement and fixation of the device.

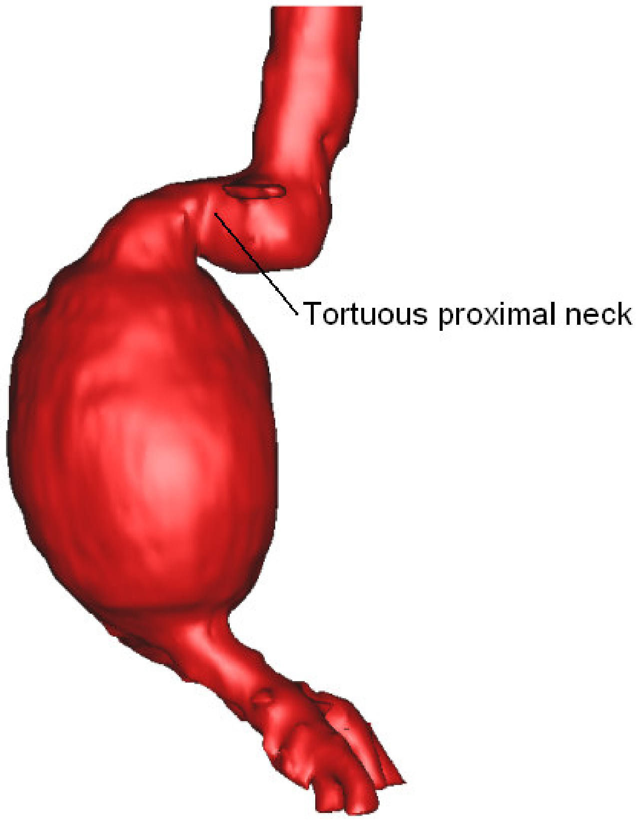

Figure 5: 3D reconstruction revealed extremely tortuous proximal neck which although can be identified using 2D CT scans, 3D reconstruction shows exactly the degree of tortuosity, thus allowing the clinician to decide on the most suitable means of approach during EVAR.

The patient-specific reconstruction shown in Figure 6 was a particularly extreme case. In this reconstruction, the full extent of the aneurysmal aorta was revealed. This patient had a descending thoracic abdominal aneurysm (TAA), abdominal aortic aneurysm (AAA) and also an iliac aortic aneurysm (IAA).

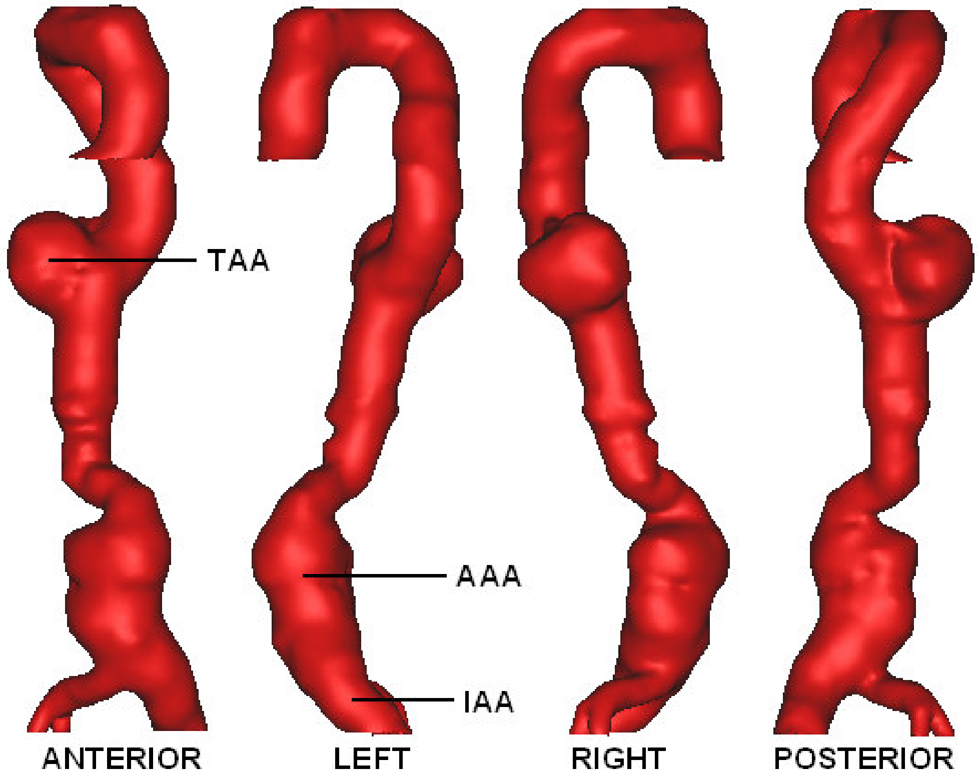

Figure 6: 3D reconstruction showing thoracic aortic aneurysm (TAA), abdominal aortic aneurysm (AAA) and iliac aortic aneurysm (IAA) from various viewpoints.

Finite Element Analysis (FEA)

The resulting wall stress distributions revealed that the TAA of this case experienced higher stresses than that of both the AAA and IAA. In this case, the peak wall stress was 1.336MPa and was located at an inflection point at the proximal region of the TAA, as shown in Figure 7. Inflection points have been previously reported to act as stress raisers on the surface of aneurysms [19,21,22,24], with inflection points defined as regions where the curvature changes from concave to convex. As the peak wall stress was computed to be 1.336MPa, the decision to repair appears justified as the failure strength of thoracic aortic aneurysmal tissue has been reported to be approximately 1.19MPa [25]. It is known that rupture will occur when local wall stress exceeds local wall strength.

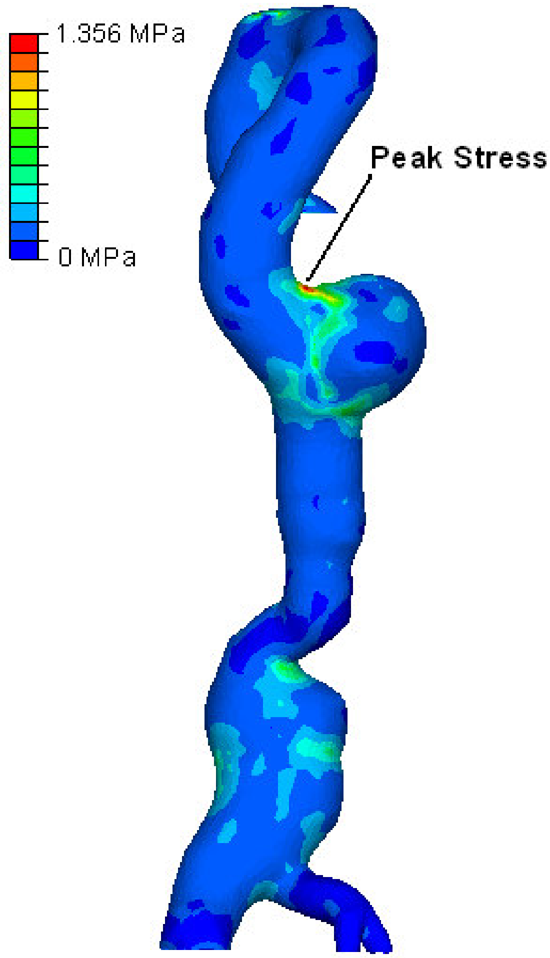

Figure 7: Resulting wall stress distribution for case examined using FEA. Peak stress was located at the proximal inflection point of the TAA. High stress is shown in red in the figure. Lower stresses were observed in both the AAA and the IAA.

Discussion

The focus of this paper was to highlight the use of 3D reconstruction as a surgical guidance tool for vascular surgeons. Currently, many clinicians use 2D CT scans to determine the correct sizing of stent-grafts and also to visualise the aneurysm prior to surgery. 3D reconstructions provide a useful addition to 2D measurements for stent-graft sizing, and therefore can possibly help improve the outcome of EVAR. This increases surgical confidence in the operation, as the clinician will not encounter any unforeseen geometrical obstacles to the already difficult procedure. Measurements obtained from 2D CT scans are often accurate, in particular when measuring diameter, as the measurement must be taken in a plane perpendicular to the true lumen of the vessel. Many clinicians measure stent-graft length from 2D images as the tortuous nature of the anerysmatic aorta can often be reduced with the introduction of the stiff guide wire. A combination of the methods may provide a better approximation of the exact length, thus allowing more precise stent-graft lengths to be obtained. Measurements from the virtual 3D model however, offer further insight into the morphology of the diseased aorta. Iliac bifurcation angles can now be accurately measured in order to determine the correct stent-graft for the particular application. Also, when fenestrated stent-grafts are to be utilised, the distances between the mesenteric arteries and the renal arteries can be accurately obtained. These exact measurements can be difficult to determine from 2D images. It is also common practice to use a graduated measuring catheter placed over the stiff guide wire prior to deployment of the device, in order to ensure the correct length stent-graft is to be introduced. Reconstruction times can vary depending on the complexity of the case. Most reconstructions can be performed under 1 hour, which should be adequate as the majority of CT scans are taken a *considerable time* prior to the actual operation. Therefore, the clinician can often afford to examine a 3D reconstruction without sacrificing the health status of the patient.

The reconstruction shown in Figure 6 revealed a tortuous proximal neck and iliac aneurysm, both of which increase the difficulty of EVAR. Fixation of the distal end of the device in the iliac arteries is hampered by the aneurysmal or tortuous artery, and therefore, the device may dislodge and ultimately fail. Calcified or tortuous iliac arteries may also rupture upon insertion or withdrawal of the introducer. The problems associated with irregular iliac arteries were highlighted in 2003 when Guidant were forced to withdraw the Ancure stent-graft from the market [29]. The diameter of the iliac arteries is of obvious importance when sizing stent-grafts, but so too is the tortuosity, as the introducer can place large stresses on the artery wall whilst being navigated through the vessel. *These particular authors have experienced two intra-operative ruptures for this reason. Can I say this???* Nowadays clinicians are tackling more challenging anatomy with EVAR compared to recent years, and therefore, the ability to view the exact morphology of the iliac arteries has clinical relevance, and may not always be possible with 2D CT scans.

Reconstruction also gives the clinician valuable information about the aneurysm before surgery. This ensures that the clinician does not encounter any unforeseen problems upon surgical repair. This was particularly useful for cases where the aneurysm displays extreme tortuosity and curvature, like the cases presented in Figures 5 and 6. Enabling the clinician to visualise the AAA prior to surgery increases confidence in the procedure as the degree of curvature of the neck or iliac arteries can readily be determined. Extreme cases, such as that of Figure 6, highlight the advantages of 3D reconstruction as a surgical tool. From the reconstruction, precise measurements can be determined, such as length, degree of curvature, angles, and exact distances over surfaces, therefore aiding in the choice of a patient-specific stent-graft from the range currently available. Cases uschas that presented in Figure 6 may often require tailor-made stent-grafts, and the use of reconstructions aid this task. Tailor-made stent-grafts can be designed using the centrelines generated from the reconstructions, and the resulting flow patterns can be identified [30]. Clinicians will usually opt to have a range of device sizes at hand during the operation so that the correct device can be obtained in the event of unforeseen circumstances. Full examinations using 3D reconstructions can help to alleviate this worry.

3D reconstructions also allow the clinical problem to be examined using various software applications. Diseased aortas can now be modelled using complex mathematical software to determine stresses and strains experienced in the wall, and also the complex flow patterns of the blood through the diseased artery allowing for stent-graft design [30]. The results of the FEA studied here show that the aorta is experiencing a peak stress of 1.356MPa at the proximal inflection point of the TAA, which exceeds the average failure strength of tissue in this area as reported previously [25]. For this particular case, the stresses within the TAA were greater than those of the AAA, which may have contributed to the sole repair of the TAA and not the AAA by the clinician. It is also known that TAAs can be more lethal than AAAs, which may have also influenced the decision of the clinician. FEA also identifies hotspots on the diseased aorta that may indicate possible rupture sites *in vivo*. The reconstruction of the stent-graft after placement within the TAA can be seen in Figure 8. The device now excludes the region of high stress and thus aids to return the aorta to a state that is relatively safe from rupture. This reconstruction was generated from post-operative CT scans that help to monitor the diseased aorta, and help highlight any additional aneurysm growth from endotension [14], or further progression of the AAA. Post-operative 3D reconstructions can also aid the clinician to observe the outcome of the EVAR procedure at regular intervals. Stent-graft limbs can often become kinked, twisted or occluded by thrombosis [17], which can complicate the flow of blood and may require further intervention by the clinician. Although these complications can be identified using 2D CT scans, 3D reconstructions allow exact visualisation of the problem and aid towards a better understanding of the overall situation of the patient.

Figure 8: Post-operative EVAR illustration showing deployed TAA stent-graft excluding TAA sac. Stent-graft now returns blood flow in the descending aorta to a relatively normal state. Transparency of the aorta in the image allows easy visualisation of the device. Model shown from the posterior viewpoint.

Conclusion

3D reconstruction of AAAs is a powerful and useful surgical guidance tool. Reconstruction allows the clinician to obtain measurements useful for the sizing of stent-grafts, and also allows the clinician to visualise the aneurysm prior to surgery. Reconstructions are also necessary for further use with FEA which has been shown to be a good method of determining wall stress in the diseased aorta. FEA provides an additional source of information to the clinician and helps towards a greater understanding of the biomechanical behaviour of the anatomy prior to surgery. 3D reconstruction is quick to perform and could aid surgeons in improving the treatment of AAAs.

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