Simulation-based diagnostic software for aortic aneurysms shows promise

IMAGINE

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Proteolytical degradation of the aorta's elastin and collagen determines aneurysm disease, and to date no proven therapeutic strategies are available, either to limit aneurysm growth or to prevent them from rupture. Hence, evaluating rupture risk is critically important in reducing aneurysm-related mortality without unnecessarily increasing the rate of elective repair. Clinical methods are somehow limited, and according to the current practice, rupture risk is (mainly) estimated from the aneurysm's maximum diameter and/or expansion rate; an approach motivated from statistics but known to fail often in individuals.

In contrast, recent research has demonstrated that patient-specific biomechanical simulations can provide more reliable diagnostic parameters and different biomechanical models are discussed in the literature. However, many approaches still suffer from modelling limitations and severe inter-operator variability. Motivated by that clinical need A4clinics, an analysing tool facilitating a comprehensive structural analysis of aortic aneurysms, has been developed.

Methods

A structural analysis of the aneurysm relies on detailed numerical (hypothetical) models and their generation currently involves a number of different software products. Such analysis is time consuming and requires expert knowledge from different disciplines. In contrast, A4clinics facilitates fast processing by integrating the latest concepts of medical image processing, vascular biomechanics and scientific computing.

Image reconstruction

Specially developed active contour (deformable) models support an artifact-insensitive segmentation of image data, which is a fundamental requirement to provide computational grids for a meaningful biomechanical analysis (Fig. 1). Based on the derived segmentation data a novel mesh generation algorithm splits the aneurysm tissue, i.e. wall and thrombus into a finite number of hexahedral-dominated volume (finite) elements, which supports an accurate structural analysis while limiting the computational effort.

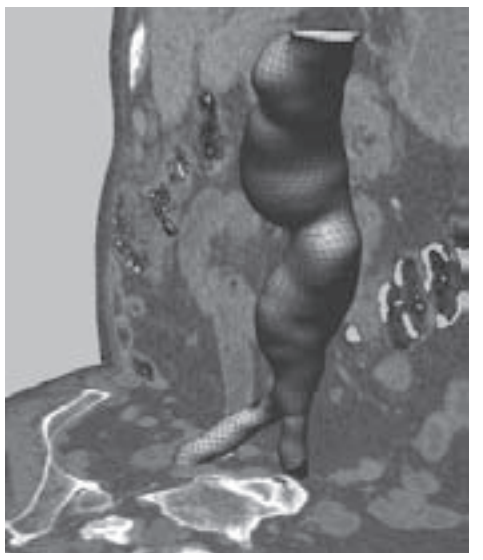

Figure 1: Patient-specific model of an abdominal aortic aneurysm reconstructed from Computer Tomography images. Image segmentation is based on deformable (active) contour models proven to be insensitive to image artifacts.

Finite Element Model

Finally, the meshed (discretised) aneurysm is enriched by patient-specific information to render a Finite Element problem[1] and hence, facilitating a structural analysis by providing detailed information about biomechanical field variables like stress and strain (Fig. 2). In details, mean arterial pressure is prescribed and constitutive models for aneurysm wall and thrombus are used as proposed in the literature. Likewise, the patient's age, gender and family history are used to estimate spatially varying wall strength; again according to results from in-vitro experiments reported in the literature. Hence, the applied assumptions enrich known biomechanical aneurysm models in several aspects and more reliable conclusions are expected.

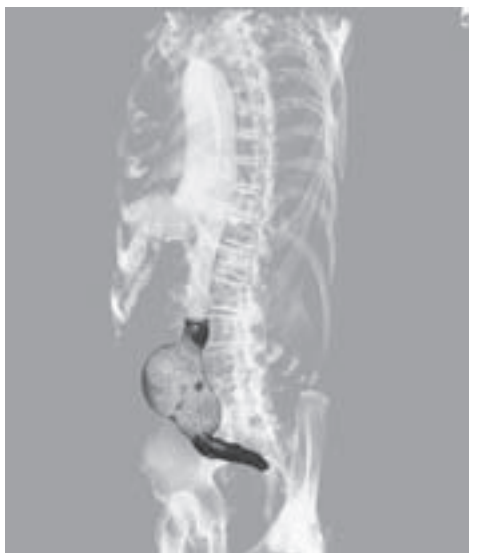

Figure 2: Patient-specific prediction of the mechanical stress in the wall of an abdominal aortic aneurysm. Structural analysis is based on a detailed Finite Element model including aneurysm wall and intraluminal thrombus.

Validation

In cooperation with the Department of Vascular Surgery at Karolinska Institute, Sweden, the proposed software tool was used to investigate the reliability of the biomechanical rupture risk hypothesis by comparing ruptured (n=10) and diameter-matched non-ruptured (n=10) aneurysms. The study revealed that peak wall stress and peak wall rupture risk (stress related to strength) were respectively *1.18* times (*p=0.091*) and 1.73 times (*p=0.022*) higher in ruptured than non-ruptured aneurysms. Most interestingly, all non-ruptured aneurysms exhibited a peak wall rupture risk below 1.0, tough to be the theoretical limit of rupture. Peak wall rupture risks of seven ruptured aneurysms were clearly elevated with respect to the non-ruptured group, whereas in three formations this was not the case. Assuming intact thrombi of these aneurysms could not explain aneurysm rupture and by relaxing that, i.e. considering thrombus perforation, (as partly indicated by the image data) finally rupture could be predicted.

Conclusions

A novel procedure to develop structural Finite Element models of aortic aneurysms was implemented in A4clinics; a stand-alone software tool to be operated without engineering skills. The computer programme is highly automated and facilitates the extraction of various geometrical and biomechanical determinants from routinely taken clinical data. The software is entirely feasible for analysis of realistic patient-specific models on standard personal computers, and hence can easily be integrated into routine clinical dataflow.

First validation studies underline the device's suitability to estimate the rupture risk of abdominal aortic aneurysms and to enhance current diagnostic methods; it might be a promising enrichment in aneurysm screening programmes, (potentially) capable of identifying rupture-prone aneurysms. Likewise, the software facilitates in-depth investigation of aneurysm biomechanics and might provide useful data from a purely scientific perspective to enrich today's knowledge of aneurysm pathology.

Acknowledgments

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[1] *The Finite Element Method is a widely applied numerical concept to solve problems in engineering and applied sciences.*

How volumetric analysis quantifies therapeutic response of slow-flow vascular malformations

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Slow-flow vascular malformations, such as venous and lymphatic lesions, are most often recognised in infancy and are thus characterised by a rapid expansion. The majority of these lesions are found in the head and neck region, where many options for treatment modalities (drug therapy, percutaneous sclerotherapy, surgical resection) have been reported in the literature. In many cases, excellent results have been achieved by ultrasound-guided or fluoroscopy-guided percutaneous sclerotherapy, sometimes combined with final surgical resection (see figure). Diagnostic MRI of vascular malformations allows non-invasive treatment planning and follow-up, with excellent soft-tissue contrast.

However, due to the spatial complexity of vascular malformations, in many cases, treatment follow-up and quantification of therapy after sclerotherapy can be difficult, and, in some cases, might be inaccurate. Nevertheless, accurate volumetric analysis to calculate the required amount of sclerotic agent and to evaluate the success of sclerotherapy is necessary.

In clinical routine, a common and convenient way to estimate the volume of a lesion is to multiply the largest diameter (in cm) in all three orthogonal axes, and divide that by two, which results in volume expressed as cm^3. This simple calculation, however, does not reflect complex, geometrically configured malformations and does not reflect subtle changes in lesion volume after sclerotherapy.

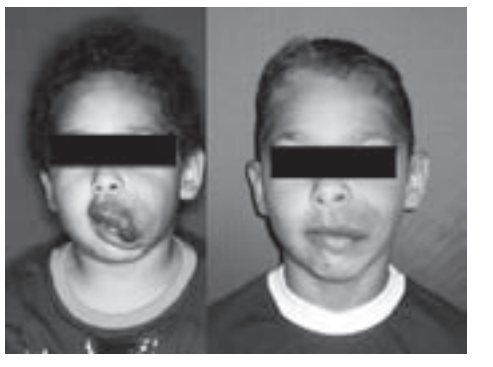
To overcome this limitation, accurate volumetric analysis can be achieved by using segmentation, and creating 3D models based on imaging data acquired by MRI. For this purpose, post-processing software and unique features, such as the ability to create 3D models and measure volume, can be used. Several powerful image processing software programs for 3D volumetry can be selected from the NIH Clinical Center (http://www.cc.nih.gov/cip/software.html), many of which are available as shareware or freeware.

We have recently compared the volume of lymphatic or venous vascular malformations in the soft tissue of the face and the extremities using a standard formula ((x*y*z)/2), and with two different volumetry software applications, including the 3D-SLICER volumetry software (Surgical Planning Lab, Harvard Medical School, Boston, US), and OSIRIS software (Digital Imaging Unit,University Hospital of Geneva, Switzerland).

The time needed for all three methods was registered and compared. Before sclerotherapy, the average volume of malformations, as calculated by the standard formula, exceeded the average volume as evaluated by 3D-Slicer and OSIRIS by 19.6%, and 21.5%, respectively. After sclerotherapy, the average volume of malformations, as calculated by the standard formula, exceeded the average volume as evaluated by 3D-Slicer and OSIRIS by 3.0%, and 16.9%, respectively. Compared to 3D-Slicer and OSIRIS software, the standard formula method overestimated the volume of malformations by 11.0% and 19.2%, respectively. The time needed to evaluate the volume was two minutes when using a standard formula, five minutes when using 3D-Slicer, and six minutes when using OSIRIS.

Each method has its advantages. The standard formula is a very quick way to roughly estimate the volume of a lesion, but one might experience some difficulties with malformations that are irregular in shape. When working with OSIRIS, the volume segmentation can only be done manually, meaning that the user has to label the lesion in every single slice in the series. This procedure is more time-consuming, but allows experienced users to distinguish between the malformation and the surrounding tissue very accurately.

When working with 3D Slicer, the user has the opportunity to use the threshold function, which may lead to quicker results, especially when the lesion and the surrounding tissue differ in gray-scale values. On the other hand, mistakes can occur when the difference between the lesion and surrounding soft tissue is small and the software miscalculates by including structures that are not part of the lesion. To avoid miscalculation, high contrast between the lesion and surrounding soft tissue on the imaging study is mandatory.



A 5-year-old boy with a large slow-flow malformation of the upper lip and left midface before (left) and after (right) 6 sessions of percutaneous sclerotherapy and final surgical resection at his 6th birthday.

All in all, volumetry software applications allow precise and relatively fast evaluation of the volumetric changes in vascular malformations. This is particularly true for complex malformations that are irregular in shape.

Thus, we advocate, after an initial quick estimation of volume using the standard formula method, the use of a software application to obtain precise volumetric data.