A NOVEL APPROACH FOR ABDOMINAL AORTIC ANEURYSM LOCAL GROWTH QUANTIFICATION

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INTRODUCTION
Abdominal aortic aneurysm (AAA) growth rate is a marker for rupture risk as it potentially reflects undesirable wall remodeling that leads to wall weakening. Currently, expansion rate is measured as change in maximum diameter over time. However, expansion is not uniform and is therefore questionable if measurement of maximum diameter change over time is adequate to capture an increased localized remodeling activity. Therefore, a paradigm shift is needed for a more sensitive quantification of AAA growth, which would not only identify small non-symptomatic aneurysms at high risk and prevent rupture thus saving lives, but also reduce the cost of emergency surgeries.

One of the difficulties in quantifying regional wall growth is that as the aneurysm grows it may elongate, become tortuous, and shift towards one side. Therefore, establishing correspondence of wall regions between follow up scans is not trivial. Even if the AAA is manually co-registered with its follow-up image, using landmarks such as renal arteries [1], the distance between wall surfaces obtained cannot be directly translated into regional growth.

In contrast to vascular disease follow-up studies, ongoing research in other medical fields that deal with regional growth quantification in the presence of shape alteration (e.g. cancer tumors) have exploited non-rigid registration methods. The present study aims at introducing a new, more sensitive method of AAA growth rate estimation based on regional wall surface area change. The proposed methodology is based on iterative closest point (ICP) algorithm and is validated using patient-specific AAAs and their artificially deformed follow-up models. Original and deformed surfaces were discretized into triangular surface meshes and were matched by the algorithm. A new measure of local surface growth is then computed from the distribution of element surface area change. To the best of authors’ knowledge, this is the first work that exploits vascular non-rigid registration for AAA disease follow-up.

METHODS
The method is based on open source non-rigid point cloud registration code that implements ICP algorithm for bone surface registration [2]. The code has been adapted to capture smaller deformations that may be present during arterial disease follow-up, has been validated, and evaluated. Input to the code are the triangulated surfaces referred to as Source (surface to be deformed) and Target (surface to be matched by Source). The goal is to obtain a measure of local wall surface deformation based on element area change of the registered Source surface. The code is split into two distinct phases: Phase 1: Surfaces are prealigned and a general deformation of the Source surface is performed to best match the Target using Procrustes algorithm. Phase 2: Surfaces are finely matched through local non-rigid deformation: for every point p on the Source surface, the K-nearest neighbors are considered, and each neighbor influences the displacement of p based on a Gaussian radial basis centered on p acting as weight function.

To evaluate the method, three dimensional computed tomography (CT) scans of 12 aneurysmatic aortas were used. The aortic luminal and external surfaces were segmented, reconstructed and tetrahedral volumetric mesh of wall and thrombus were obtained. Wall deformation was obtained by applying a uniform pressure in ANSYS. The displacement computed at each node of the external surface was used as reference displacement. By applying a wrap-by-vector with a scale factor from 0.5 to 7 in ParaView, a range of surface deformations were obtained for each AAA model. The Source surface was co-registered with each of the multiple Target surfaces, and results were evaluated...
using the following metrics:
- The Overlap coefficient was defined as the percentage of points on Source whose Euclidean distance from the Target is smaller than 1 mm.
- The local registration error (Reg\text{err}) is defined as:
  \[
  \text{Reg}_{\text{err}} = \text{LAC}_{\text{real}} - \text{LAC}_{\text{est}}.
  \]
  where LAG: the Local Area Change of each surface element a) due to application of nodal displacements (provided by ANSYS), LAC\text{est}, and b) due to registration, LAC\text{real}.
- To obtain a global measure of registration error for each case, an Error Index (EI) was defined as the mean plus the standard deviation of Reg\text{err}.

Mesh, Initial Distance, and Rotation Sensitivity Analysis
- The effect of mesh density on overlap coefficient was evaluated using one of the AAA models.
- To assess the effect of initial distance distribution (after prealignment) between Source and Target surfaces on registration accuracy, a Distance Index (DI) was defined as the mean value plus the standard deviation of the distance of each node between Source and Target Surfaces.
- The stability of the method with respect to rigid body motion was assessed. Towards this the Source surface of all cases was first rotated with respect to X-, Z- and both X- and Z-axes for various angles (3º-24º) and then registered to the Target surface.

RESULTS
Mesh sensitivity analysis showed that when mesh density was above 0.75 mm\textsuperscript{-2}, the overlap coefficient was < 0.60, while for mesh densities ranging between 0.15 mm\textsuperscript{-2} and 0.75 mm\textsuperscript{-2} overlap was > 0.94. Furthermore, the EI did not increase with increase of angle rotation, but presented negligible discrete fluctuations.

Initial distance between Source and Target surfaces was, as expected, inversely related to registration accuracy. As distance increased, less surface elements after registration changed their area in accordance with the computed value (from ANSYS). In order to obtain an estimate of error associated with DI, 12 test cases were registered to each of their follow-ups of different Distance Index producing a database of 157 registrations. The cases were grouped per DI range (in 1 mm intervals) with 16 to 23 cases in each group, and the mean and range of EI is presented (Fig. 1).

![Figure 1: Effect of initial distance between surfaces to the registration error. For every 1 mm of Distance Index, the mean and range (min, max) of error index are presented.](image)

Application on patient-specific follow-ups
The method was applied to surfaces generated from clinical follow-up CT scans of two AAA patients and results obtained are presented (Fig. 2). The maximum diameter of the first AAA (Fig. 2A) increased from 35 to 45 mm in 29 months, and the maximum LAC was found at the surrounding area of maximum diameter at the anterolateral region, and equal to 5.6 ± 0.2 mm\textsuperscript{2} (DI=1.72 mm, suggesting an EI=0.2 mm\textsuperscript{2}), or in terms of percentile growth 34.3 ± 3.6 %. The maximum distance between the initial and follow-up image (correspondence) at this location was 8.3 mm. Maximum diameter of the second AAA (Fig. 2B) increased from 50 to 52 mm in 12 months, and the maximum LAC was found at the distal end of the sac, below the region of maximum diameter, and equal to 2.8± 0.2 mm\textsuperscript{2}, or in terms of percentile growth 5.6 ± 2.8 mm\textsuperscript{2}.

![Figure 2: Application of method on two real AAA cases (A, B). Initial surface with distribution of local element area change and follow-up surface (grey, semi-transparent) shown.](image)

DISCUSSION
We propose a methodology based on non-rigid registration in order to obtain a detailed distribution of local vascular growth. Our results suggest that the method can offer a meaningful measure for local area change of AAA wall surface, and provide a useful tool in vascular follow-up studies.

The method was applied for two real patient cases. In the first case, maximum surface growth occurred at the region of maximum diameter. In such cases, the growth rate based on maximum diameter would capture the maximum AAA growth rate. However, in the second case, the maximum surface growth did not spatially coincide with maximum diameter change. In such case the proposed methodology offers accurate growth rate estimates based on local surface deformation analysis.

In contrast to maximum diameter based growth estimation, surface area change based growth estimates cannot be clinically interpreted and evaluated as yet. Based on the two cases analyzed here 5.6 and 2.8 mm\textsuperscript{2} surface area change correspond to local surface displacements of 8.3 and 5.5 mm respectively. It is anticipated that multicenter, large cohort clinical studies will assist in providing clinical guidelines based on both local and global surface growth values for improved rupture risk stratification.

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