MESH RESOLUTION REQUIREMENTS FOR THE NUMERICAL SIMULATION OF FLOW THROUGH STENTED ANEURYSMS

Gordan R. Stuhne (1), David A. Steinman (1,2)

(1) Imaging Research Labs,
Robarts Research Institute
London, Ontario
Canada

(2) Department of Medical Biophysics,
University of Western Ontario
London, Ontario
Canada

INTRODUCTION

The treatment of aneurysms frequently entails the implantation of stents that are designed to prevent ruptures by promoting thrombosis. A stent is constructed as a braided tubular assembly of thin metallic wires and lodged against the lumen of the parent vessel to serve as a porous barrier disrupting blood flow into the aneurysm. Previous studies (e.g., [1,2]) have attempted to quantify this effect, utilizing computational fluid dynamics (CFD) to analyze blood flow in and around stented aneurysms. However, because of the scale disparity between the stent wire cross-section and the dimensions of the aneurysm and its parent vessel, it is difficult in practice to incorporate both geometries simultaneously into the solution domain of the discrete Navier-Stokes equations. CFD analyses have hence relied upon various non-rigorous approximations that neglect the exact stent geometry.

Setting aside the very small wire cross-section, wire spacing and other dimensions of the stent are of the same order as the dimensions of the unstented flow domain. Any heuristic model of the effects of stenting is hence suspect from a fluid dynamical standpoint, and it is important to analyze how much spatial resolution is required for accurate Navier-Stokes simulations of flow through the appropriate domain. We address this question for a simple case, considering the RMS velocity magnitude within an aneurysm as a measure of its internal flow intensity, the reduction of which is the object of stenting. It is shown how simulations with relatively modest finite element mesh resolutions accurately predict the decrease of internal RMS fluid speed in an idealized aneurysm as an increasing number of discrete stent struts is placed across its throat.

METHODS

The idealized flow model is based upon the geometry of Aenis, et al [1], which assumes a 0.466 cm diameter round side-wall aneurysm attached to a 0.35 cm cylindrical parent vessel. In this preliminary study, we considered only the case of two dimensional steady flow, in which the addition of a stent to the unstented geometry simply generates small isolated gaps associated with struts. The physical

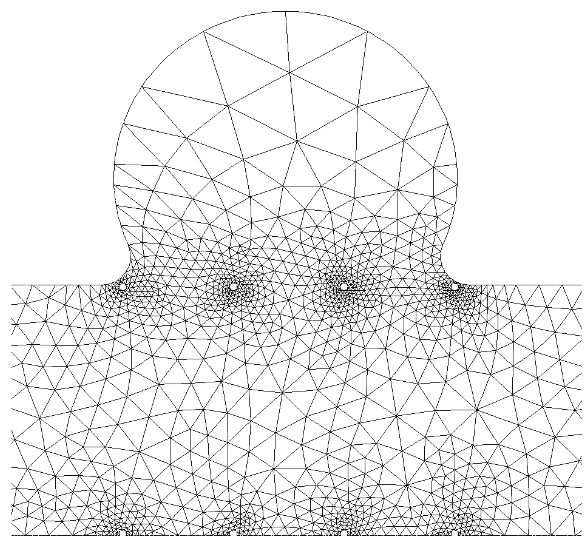

Figure 1: Mesh after 10 adaptations for geometry with 4 stent struts across aneurysm throat.

applicability of such cases is questionable, but our objective so far has simply been to establish resolution parameters for a fully three-dimensional study. A strut diameter of 0.01 cm was assumed (following Aenis, et. al.[1]), and a row of between 0 and 14 evenly spaced circular struts was added across the throat of the aneurysm. The centers of the struts were displaced into the parent vessel by 1/2 radius from the lumen, and a complementary row of struts was embedded in the wall opposite the aneurysm. The stents in all cases had the same length, the centers of the outermost two struts being horizontally displaced by 0.225 cm from the aneurysm center.

An in-house finite element code ([3]) was used to obtain steady solutions of the 2-D Navier-Stokes equations at a Reynolds number of

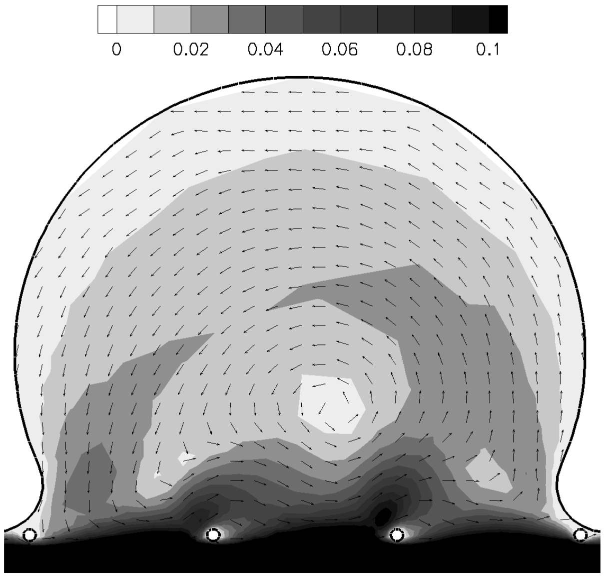

Figure 2: Velocity amplitudes (contours) and directions (vectors) in aneurysm body.

250 (based upon the parent vessel diameter). The solver is based upon the penalty function method and makes use of quadratic Crouzeix-Raviart elements. The present study also made use of a non-standard mesh generation algorithm. Meshes were generated by an advancing front technique ([4]), which begins from an exact boundary and permits the specification of a target mesh density at each point in the domain interior. The mesh density field was calculated by an iterative adaptive procedure in which the density is computed from the flow field of the previous iteration in such a way as reduce local and global errors in the strain rate (as quantified by a 2D implementation of the error estimator described by Prakash and Ethier[5]). No interpolation was used for the flow fields, and a new steady solution was obtained at each mesh generation step.

RESULTS

Fig. 1 illustrates the mesh obtained after 10 adaptations for the case with 4 struts across the aneurysm throat. The ends of the parent vessel are about 3 diameters away from the portions shown. Close inspection of the grid near the struts establishes that the node-to-node spacing (or half the quadratic element edge length) is about one strut radius. Fig. 2 shows the contoured amplitude and vector direction of the steady velocity field within the aneurysm body. The amplitudes are given as a fraction of the maximum inflow speed, and it should be noted that the low velocity around the struts ensures that the local Reynolds number is significantly smaller than the nominal global value of 250.

In Fig. 2, we plot the RMS value of the velocity amplitude within the aneurysm as a function of the number of struts across the throat (0 struts being the unstented case). Results are shown after 5 and 10 grid adaptations, and for a high resolution case in which the grid of the latter case is uniformly subdivided. It is seen that this measure of flow intensity is consistently predicted in all cases, and decreases with the number of struts as expected.

CONCLUSIONS

We have shown that the RMS flow speed in stented aneurysms is accurately captured with a quadratic finite element mesh having node-to-node spacings of about one stent strut radius for several layers around the struts. Similar resolutions will likely be adequate for the analogous three-dimensional case. Other flow quantities such as strain rate are less accurately represented, and are expected to require finer global resolution. It is only in the high resolution limit that our computed strain fields near the wall-embedded stent struts qualitatively resemble those illustrated in Berry, et. al.[6].

Another issue to be considered in further work is the effect of larger local Reynolds number near the struts, as occurs in non-side-wall aneurysms where the parent vessel flow impinges directly upon the struts.

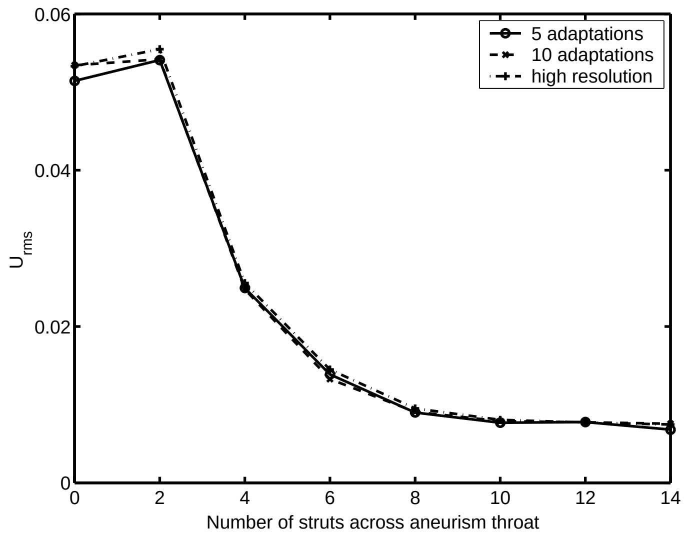

Figure 3: Variation of the RMS velocity amplitude in an idealized aneurysm with the number of stent struts across the aneurysm throat.

ACKNOWLEDGEMENTS

Supported by grants from the Canadian Institutes of Health Research (MPO-53185) and the Whitaker Foundation (RG-01-0219). DAS was supported by a New Investigator award from the Heart and Stroke Foundation of Canada.

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