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Computational Study of Stented and Wrapped Aortic Aneurysms

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Abstract: Aortic aneurysm is a pathology that involves the enlargement of the aortic diameter and has risk factors including aortic dissection. Aneurysm wrapping and stent placement has been used in the treatment of aneurysms. This study aimed to investigate the biomechanical effects of wrapping and stenting on aneurysm. The three-layered aortic aneurysm were created and fluid structure interaction were simulated in wrapped model and stented model. The results provide quantitative predictions of flow patterns and wall mechanics as well as the effects of wrapping and stenting.

1 Introduction

An aneurysm is an irreversible enlargement of an portion of an artery greater than 50% of its nominal diameter, related to weakness in the wall of the blood vessel. As the aneurysm expands, it may eventually rupture. The traditional treatment requires open surgical repair, which involves an incision and exclusion of the diseased aneurysm with a synthetic graft.

An alternative treatment is endovascular aneurysm repair. It is now recognized as an effective alternative to conventional open surgery since it was first introduced into the clinical practice in 1991[1,2]. This is the minimally invasive technique of inserting a stent into the aneurysm site via the femoral and iliac arteries. Clinically it has been shown that aneurysms can still expand after endovascular aneurysm repair without the presence of endoleak [3].

Wrapping of intracranial aneurysm has been performed since 1933 when Dott used hammered muscle to form a secure scaffolding for clot and fibrosis around the

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aneurysm [4]. Progress in micro-neurosurgery, clip technology, and endovascular treatment have relegated wrapping to the role of an almost obsolete technique. However, in some cases, the neurosurgeon may encounter aneurysms that defy clipping, and where wrapping may seem the only possible treatment. It is not possible from the conflicting data in the literature to know whether wrapping gives any protection [5,6,7] against rupture.

Numerical modeling of aneurysm is a useful method for determining the stresses. Finite element analysis allows the stresses on the aneurysm wall to be determined [8,9]. Fluid-structure interaction of aneurysms, though still an emerging field of study has seen an increasing number of publications in recent years. However, there has been little work published on the effect of stent and wrapping on aneurysm wall stress. The objective of this work was to investigate the effects of stenting and wrapping on aortic aneurysm with the use of fluid structure interaction. The stented aneurysm model and the wrapped aneurysm model were utilized in the study, which aims to provide a non-invasive methodology for quantifying aneurysm wall mechanics.

2 Methods

2.1 Geometry

The stented aneurysm model and the wrapped aneurysm model were generated with the commercial software Comsol (version 4.0a, Comsol, Inc., Burlington, MA, USA). Fig. 1 shows the axisymmetric geometric models of stented and wrapped three-layered aneurysms. The dimensions of the model aneurysm are: inlet radius r=12 mm; maximum aneurysm radius, R=30mm; total length of the aneurysm segment, L= 75mm. Because wall thickness was not studied in this investigation, it was assumed to be uniform throughout at 2 mm. An average thickness ratio of intima/media/adventitia of 13/56/31 for arteries was observed in Schulze-Bauer's studies [10] . The thickness ratio of media/adventitia is 2/1 in the computational model for the arterial wall presented by Driessen et al. [11] . In this three-layered wall model, the intima/media/adventitia thickness ratio was set to 1/6/3. Therefore, the thicknesses of the intima, media, and adventitia in aneurysm models were t_i = 0.2 mm, t_m = 1.2 mm, and t_a = 0.6 mm, respectively. The vessel walls modeled as axisymmetric solid.

In the stented aneurysm model, the stent covered the aneurysm segment. The stent was represented by a simple circular wires with wire diameter d=1.0mm. The stent has a total length *l*=90mm, and *n*=10 braids. The center of stent was chosen to lie on the center of the aneurysm. The stent wire diameter is much smaller than the vessel diameter [12].

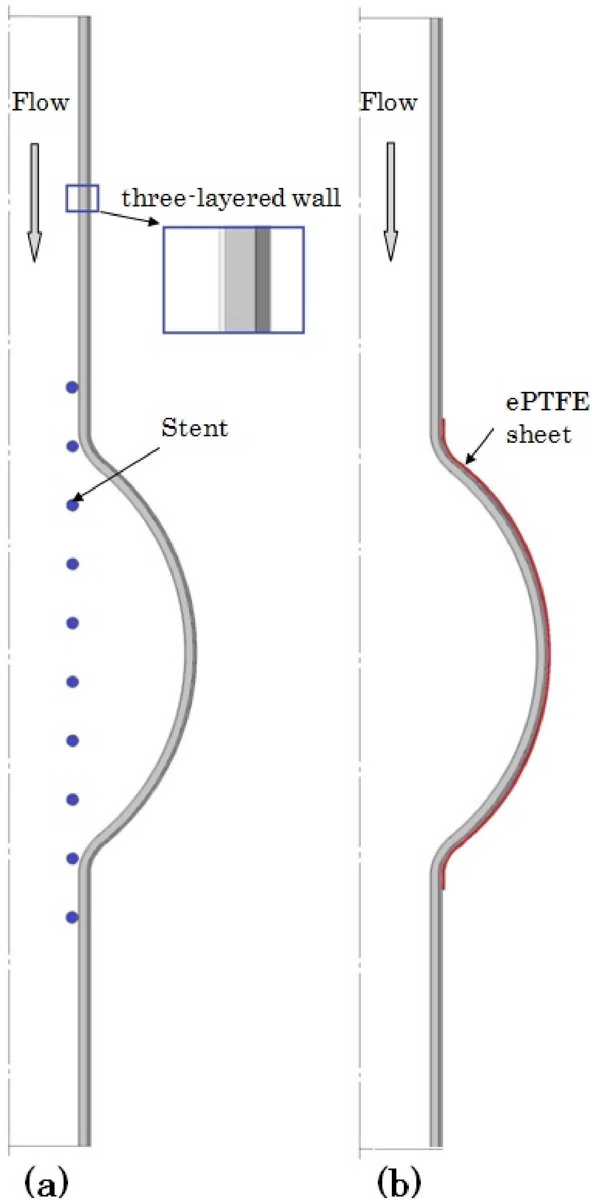


Figure 1: (a) Axisymmetric stented aneurysm model with three-layered wall (b) Axisymmetric wrapped aneurysm model with three-layered wall

In the wrapped model, the surface of outwall of aneurysm was covered by an expanded polytetrafluoroethylene (ePTFE) sheet of 100μm [13].

2.2 Governing equations and boundary conditions

The flow is assumed to be laminar Newtonian, Viscous and incompressible. the Navier-Stokes equations in Arbitrary Lagrangian-Eluerian (ALE) formulation are uses as the governing equations:

$$\rho_f \frac{\partial \mathbf{u}}{\partial t} - \nabla \cdot \left[(-p)\mathbf{I} + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u}))^T \right] + \rho_f \left((\mathbf{u} - \mathbf{u}_m) \cdot \nabla \right) \mathbf{u} = \mathbf{F} - \nabla \cdot \mathbf{u} = 0$$

where ρ_f is the fluid's density, u is the velocity field of the flow, p is the fluid pressure, I is the unit diagonal matrix, F is the volume force affecting the fluid, u_m is the mesh velocity due to the movement of the coordinate system. Assume that no gravitation or other volume forces affect the fluid, so that F=0. The common frame time derivative, valid for a fixed point in the frame on which the variable is defined. For example, for w defined on the spatial frame:

$$w_t\left(x_0,\, y_0\right) = \left.\frac{\partial w}{\partial t}\right|_{x_0, y_0}$$

The mesh time derivative, which is taken for a fixed point in the mesh:

$$w_{\mathrm{TIME}}\left(X_m,\, Y_m\right) = \left.\frac{\partial w}{\partial t}\right|_{X_m, Y_m}$$

so, mesh velocity u_m is (x_{TIME}, y_{TIME}). Blood is modeled to have a density ρ_f=1050 kg/m3 and a dynamic viscosity μ=0.0035 pas. The structural deformations are solved for using an elastic formulation. The wall experience a load from the fluid, given by

$$\mathbf{F}_{\mathrm{T}} = -\mathbf{n} \cdot \left(-p\mathbf{I} + \eta \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right)$$

where **n** is the normal vector to the bounday. This load represent a sum of pressure and viscous forces.. The aneurysm wall is¡¡assumed to be an isotropic, linear, elastic solid with a density ρ_s=2000 kg/m^3, a Poisson's ratio =0.45, and mean Young's modulus E=4.0 MPa. The Young's modulus of the intima, media, and adventitia are 1.6, 4.8 and 3.2 MPa respectively.

The boundary condition at inlet is set as a steady flow with a constant velocity of 0.27 m/s (Reynolds number of 1950) in normal direction, while the boundary condition at outlet is a free outflow, with the pressure of 120.3 mmHg, and no-slip condition was applied to the wall and the stent. The inflow with a Reynolds number of 1950 was applied at eh inlet of the fluid domain and the pressure of 120.3 mmHg was set at the exit of the fluid domain. For the composite structure, the boundary conditions include fixed displacements at the inlet and the exit, and free displacement of the wall. The stent is assumed to be rigid and fixed and the ePTFE sheet is adhered firmly to the surface of the aneurysm wall. Young's modulus of 54.58 MPa and density of 583.25 kg/m^3 used in the analysis for medical grade ePTFE was obtained by means of tensil tests [14].

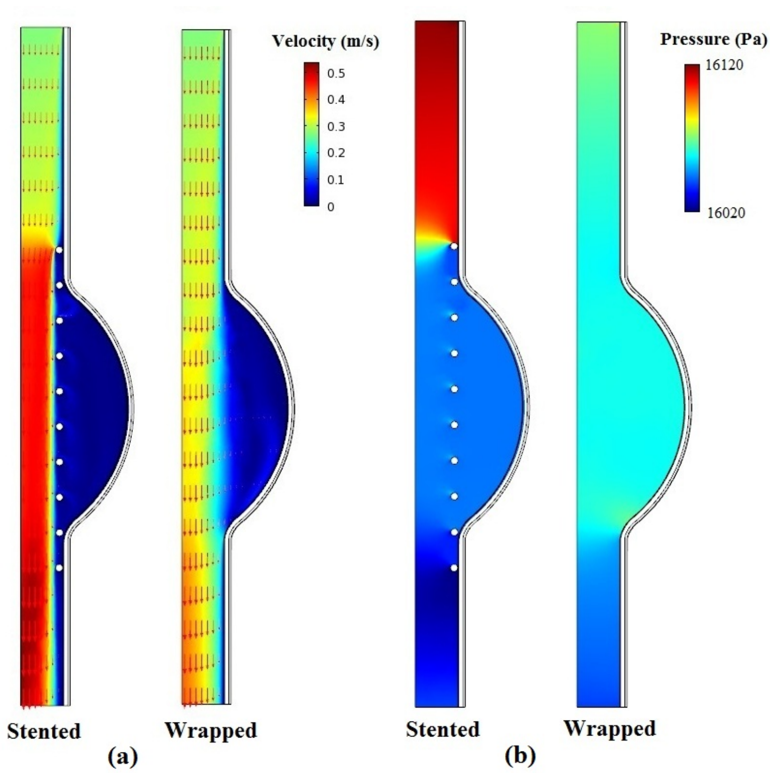


Figure 2: Comparison of flow velocity and pressure distribution in stented aneurysm and wrapped aneurysm: (a) Velocity (b) Pressure

3 Results

Computations were performed for the stented aneurysm model and the wrapped aneurysm model under steady flow condition. Details of our findings are given below.

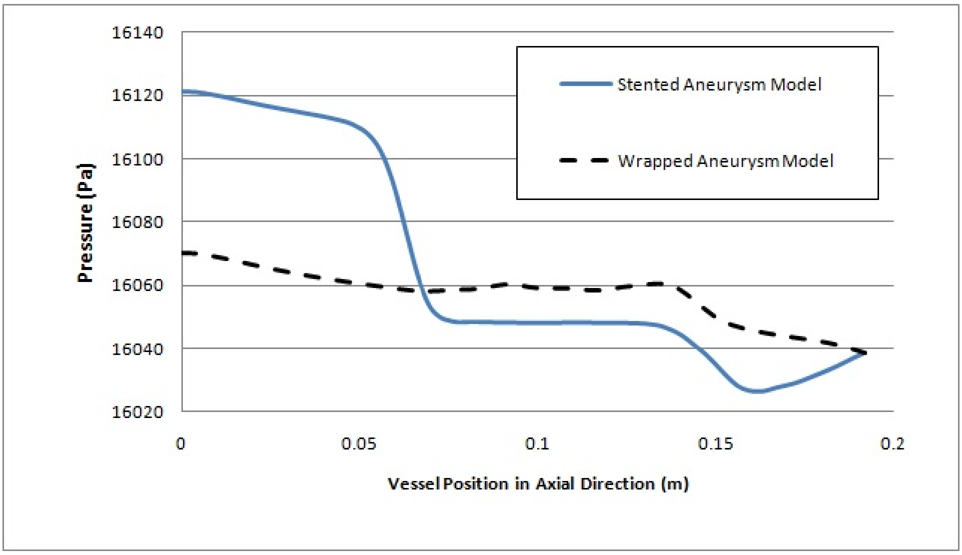


Figure 3: Pressure distributions along the center axis in stented aneurysm and wrapped aneurysm.

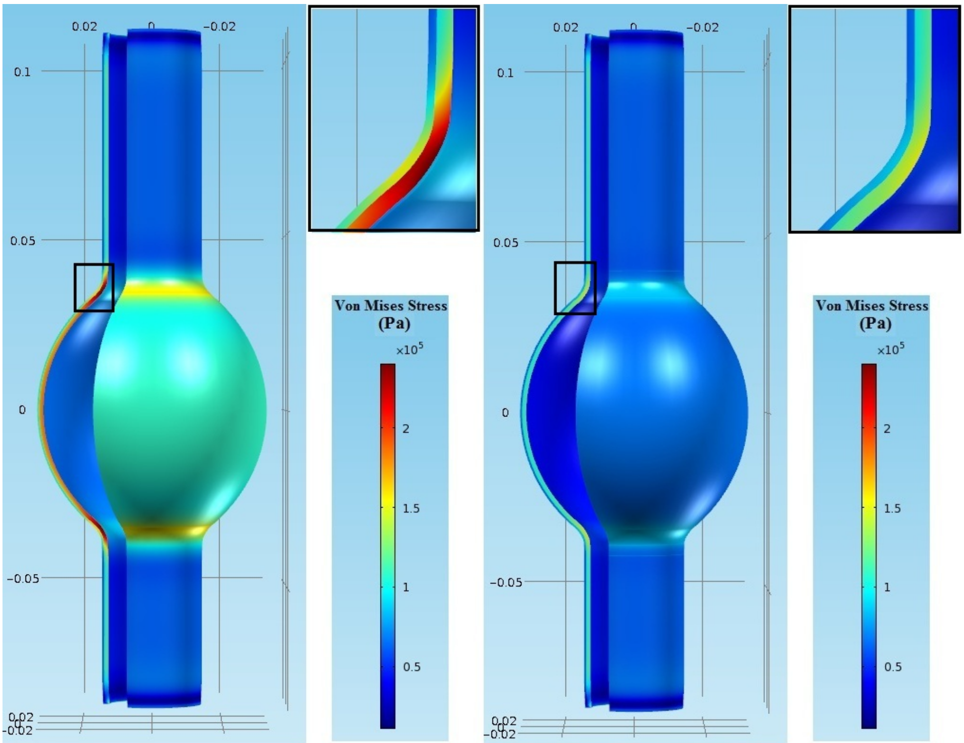
3.1 Velocity and Pressure

Fig. 2 shows the flow velocity and pressure distribution in the stented aneurysm model and the wrapped aneurysm model. In the vessel section, the flow is more or less uniform due to the vessel section is straight and the flow is steady. The velocity in the proximal neck between the two models is nearly identical, but in the inflated region the velocity magnitude was greater inside the aneurysm in the stented model than the wrapped model. The pressure in the proximal neck is higher in the stented model than the wrapped model, however, the pressure in the inflated region is lower in stented model than the wrapped model.

Fig.3 shows the pressure distributions along the center axis in stented aneurysm and wrapped aneurysm. The pressure gradient is highest at the inlet in the stented anearysm model and lower in the inflated region and distal neck than in the wrapped aneurysm model. Within the inflated region, the pressure is almost uniform distributed in the inflated region both in the stented aneurysm and wrapped aneurysm.

3.2 Wall stress

The¡¡von Mises stress distribution on the aneurysm model was plotted and observed. Stress is a tensor quantity with nine components. The von Mises stress is a stress index especially suited for failure analysis and is a combination of these



(a) Stented model **(b) Wrapped model**

Figure 4: Von Mises stress distribution in stented model (a) and wrapped model (b).

nine components. Studying the von Mises stress, rather than each component of stress, allows for meaningful interpretation of the results. The von Mises stress distribution in the stented model and the wrapped model is shown in Fig. 4. Both peak stresses occur in the media layer at the inflection region, and the stresses at the midsection are higher than proximal neck and distal neck. The wall stresses on proximal neck and distal neck were very similar between the stented model and the wrapped model. However, the stresses are much higher in the stented model than the wrapped model. Fig. 5 shows Von Mises stress distribution across wall thickness at inflection points in stented aneurysm model and wrapped aneurysm model. The maximum Von Mises stress in the stented model was found to be 243,932 Pa. This was reduced by 37% to 151,611Pa in the wrapped model.

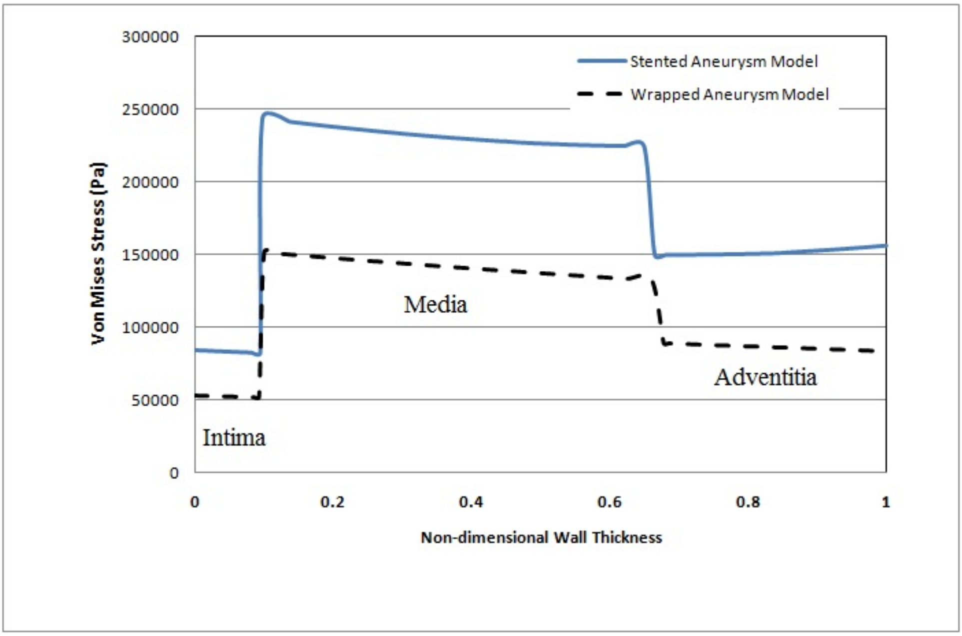


Figure 5: Von Mises stress distribution across wall thickness at inflection points in stented aneurysm model and wrapped aneurysm model.

4 Discussion

Fluid structure interaction of a stented aneurysm and a wrapped aneurysm was simulated. Aortic aneurysms remain a challenging problem for every surgeon even in the current time of advanced surgical procedures and endovascular alternative techniques for the treatment of aortic pathologies. The wrapping technique is a surgical technique used under certain circumstances in case of ascending aorta dilatation.

Most previous work has investigated numerous parameters in a stented model based on CT scans [15-18]. It was observed that peak wall stress is reduced 20 fold in a stented aneurysm [15]. In a patient specific stented FEA model a 90% decrease in aneurysm wall stress was reported [19]. Our results compare the effects of stenting and wrapping on the flow as well as the wall stress. The peak von Mises wall stress on the aneurysm was reduced by 37% in the wrapped model comparing with stented model.

Our results shows the hemodynamic changes after stenting and wrapping. Previous studies have been performed to investigate the hemodynamic effects of stenting on aneurysm. Zhang et al. [20] found that stenting significantly changed the blood flow pattern and the vortexes in the aneurysm reduced or even disappeared. Clen et al. [21] devised an experiment to study the flow in stented aneurysm. They used angiographic methods to reveal that stents altered flow within the aneurysmal lumen by providing a mechanical hindrance to the usual flow patterns while maintaining patency of the native lumen. Our results are in agreement with these observations. Stents blunted the flow for protection of weakened aneurysmal wall and increased the pressure gradient at the inlet. Stent implantation will lead to a decrease in maximum wall pressure inside the aneurysm sac.

Wrapping of intracranial aneurysm has been performed since 1933 when Dott used hammered muscle to form a secure scaffolding for clot and fibrosis around the aneurysm [4]. This wrapping method has been widely used to obtain hemostasis and reinforcement of the anastomotic site [22].

Recent advances in endovascular treatment [23] can sometimes be helpful, but remain at the moment inadequate for these difficult aneurysms. Re-inforcing the aneurysmal sac with some form of wrapping or coating seems sometimes the only possible way of treatment. Several types of material have been used for wrapping. Autogenous material such as muscle, fascia or dura mater have been shown to adhere only slowly to the aneurysmal wall, giving inadequate early protection, and to be absorbed in the long term, giving poor long-term results[24-29].Cotton derivatives, e.g., gauze and muslin, showed a better experimental adherence [25,29], good results in some[30,31] but a high incidence of rebleeding in other clinical studies [24,26], and were associated with optochiasmatic arachnoiditis and granuloma formation[32-34]. Ujiie et al. developed a newly improved ePTFE by ion beam irradiation technique that is biologically inert and able to firmly adhere to surrounding tissue and had a good clinical result [13]. The wrapping increases the thickness of the aneurysm wall and increases the strength of the vessel wall [35,36]. Our results showed wrapping decreased the peak wall stress in aneurysm and gave the protection against rupture comparing with stent treatment.

In this study it was assumed that the aneurysm wall is homogeneous, isotropic, and linearly elastic, which is not the case. However, this study provided a first comparison of the effects of stenting and wrapping, which is the goal of this study. We also assumed that the mechanical properties and thickness of the aneurysm wall are uniform. This is not realistic because of localized calcifications. Experimental sampling of wall specimens reveals that the wall is actually non-uniform, thinning in response to pulsatility and the progressive expansion of the aneurysm sac [37]. In the future, we plan to include a variable arterial wall thickness in the simulations.

Fluid-structure interaction of a stented aneurysm and a wrapped aneurysm was simulated. The velocity and pressure were examined as well as wall stress. Our results compare the stented aneurysm model with the wrapped aneurysm model. Stenting protects the weakened aneurysm wall from blood flow and high pressure. Despite of higher pressure, the peak stress in media layer in wrapped aneurysm was smaller by 37% than the stented aneurysm. To draw a definitive conclusion, the wrapping method may be an effective alternative to surgery for treatment of aneurysm.

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