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Original Article

Solid and Poroelastic Models of Intraluminal Thrombus Using Finite Element Method

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Abstract *- The porosity of intraluminal thrombus will be examined in this study, and the results will be compared to those of solid intraluminal thrombus. Two three-dimensional models were used in this investigation. The first used poroelastic material, and the second used solid material. The findings of the present study revealed that the difference in wall stresses gained from the three situations is negligible (about 2.2%) based on the two models examined. The distribution of wall stress and the position of greatest stress remain unchanged. In summary, if maximal wall stresses are needed, the porosity of intraluminal thrombus may be ignored because there is little effect of using porous media for intraluminal thrombus on the maximum value and distribution of wall stresses.*

Keywords *- Abdominal aortic aneurysm, Aortic rupture, Finite element analysis, Intraluminal thrombus model.*

1. Introduction

The introduction should be succinct, with no subheadings. Limited figures may be included only if they are truly introductory and contain no new results. The ILT of AAA is a porous material with an average porosity of 80% (Ashton et al., 2009), however, most finite element studies assumed it as a solid material for simplification purposes. This simplification method will be examined here to assess the value of implementing porosity in the ILT material. While intraluminal thrombus within abdominal aortic aneurysm is a very porous substance with an average porosity of 80%, earlier research believes it to be a solid material for simplicity reasons [1]. A limited number of numerical studies have used finite element models to investigate the porosity of intraluminal thrombus [2-4]. These studies have yielded valuable insights into the effects of thrombus porosity on the biomechanics of abdominal aortic aneurysms. Furthermore, Meyer et al. (2010) mimicked porosity by applying trans-thrombus blood pressure; since intraluminal thrombus does not lower blood pressure [5], they applied the pressure directly to the wall beneath the thrombus without modelling the porous intraluminal thrombus material.

While Avinash et al. [2] employed the fluid phase of a porohyperelastic model to provide some information on blood flow within intraluminal thrombus, Meyer et al. [5] and Polzer and Bursa [3] overlooked the real dynamics of blood flow in their studies. The potential contribution of simulating the intraluminal thrombus porosity to the comprehension and evaluation of abdominal aortic aneurysms is still unknown. The present study will investigate the porosity of intraluminal thrombus and compare the findings with those of solid intraluminal thrombus.

2. Methodology

In the present study, 2 three dimensional models were employed. The first investigated intraluminal thrombus using poroelastic material and applied a homogeneous pressure of 145 mmHg to the blood lumen acting on the thrombus, as illustrated in Figure 1A. The second investigated intraluminal thrombus using solid material and applied pressure to the blood lumen acting on the thrombus, as illustrated in Figure 1B.

For the first case, poroelastic components based on Biot's theory [6] were used to model intraluminal thrombus as porous in the first scenario. For Biot's consolidation issues, the governing equations are:

$$\begin{cases} \nabla \cdot (\sigma' - \alpha\rho I) + f = 0 \\ \alpha\varepsilon' V + \frac{1}{k_m}\rho' + \nabla\cdot q = s \end{cases} \tag{1}$$

Where:

$\nabla \cdot$ = Divergence operator of a vector or second-order tensor

σ' = Biot effective stress tensor

α = Biot coefficient = 1

ρ = Pore pressure

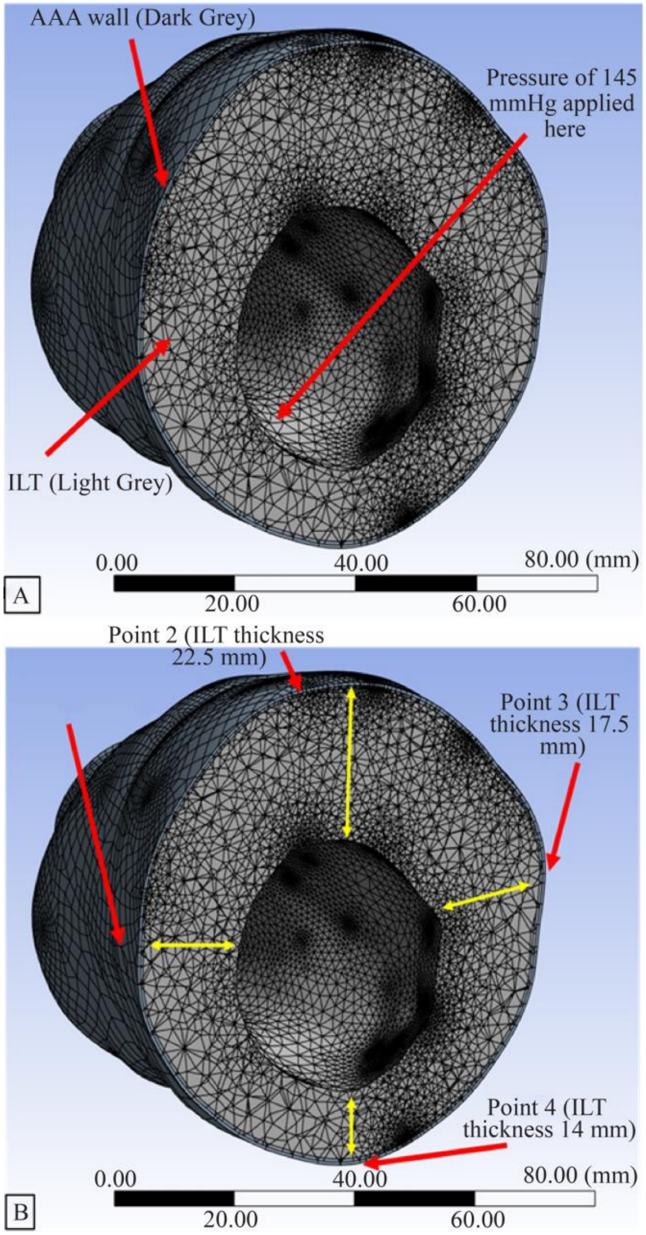


Fig. 1 (A) Method of applying the pressure on intraluminal thrombus & (B) Four points on the wall were selected to compare the resulting stresses

I = Second-order identity tensor

f = Body force of the porous media

$\varepsilon' V$ = Elastic volumetric strain of the solid skeleton

Km = Biot modulus

q = Flow flux vector

s = Flow source

The relationship between the Biot effective stress and the elastic strain of solid skeletons is given b:

$$\sigma' = D : \varepsilon^{e} \tag{2}$$

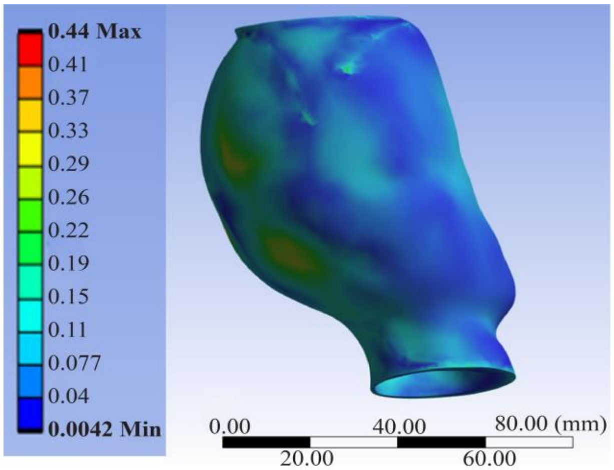
Where ε^{e} is the second-order elastic strain tensor, and D is the fourth-order elasticity tensor.

The relationship between the fluid flow flux and the pore pressure is described by Darcy's Law [7]:

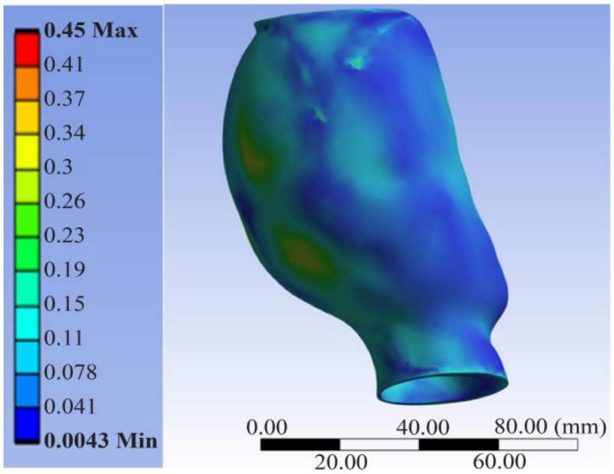
$$q = -k\nabla p \tag{3}$$

Where k is the second-order permeability tensor and ∇ is the gradient operator.

An earlier study by Adolph et al. reported an intraluminal thrombus of 0.91 ±0.54 mm4/N • s [8]. For the present study, the average value of 0.91 mm4/N • s is chosen for the permeability value of the intraluminal thrombus. The Young's modulus of 0.11 MPa and a Poisson's ratio of 0.45, the solid phase of the intraluminal thrombus in the first case and the solid intraluminal thrombus in the second and third cases were treated as linear elastic. As seen in Figure 1B, four spots on the wall were chosen in order to compare the ensuing stresses.



A: Solid ILT



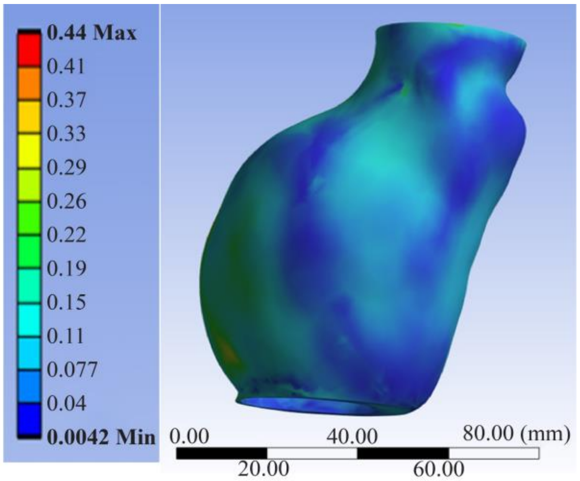
B: poroelastic ILT

Fig. 2 Right view of abdominal aortic aneurysm wall

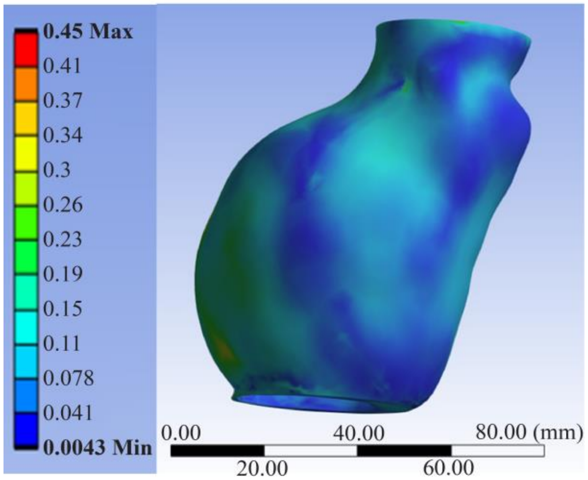
3. Results

The Von Mises stress distribution [9] for the two models (intraluminal thrombus and porous intraluminal thrombus) derived from static simulations of the peak systolic pressure is shown in Figures 2 (A & B) for the right view of the wall.

In Figure 3 (A & B), the Von Mises stress distribution for the two models (intraluminal thrombus and porous intraluminal thrombus) derived from static simulations of the peak systolic pressure for the left view of the wall.



A: Solid ILT

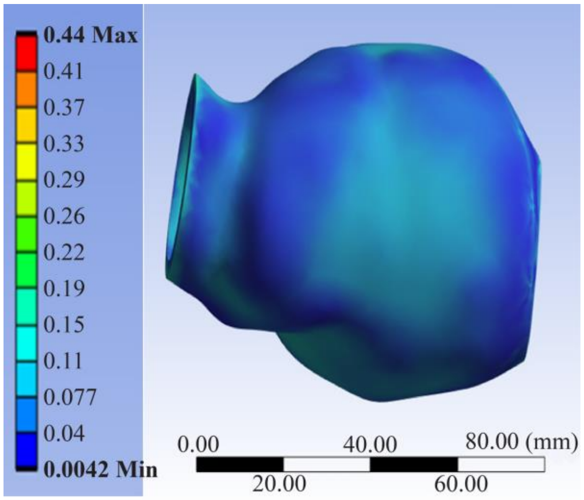


B: poroelastic ILT

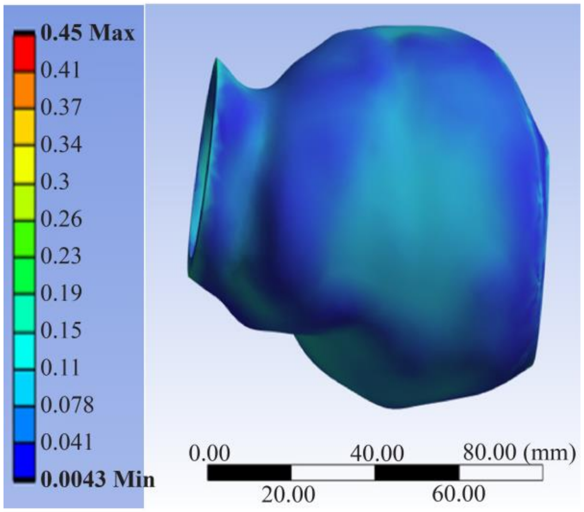
Fig. 3 Left view of abdominal aortic aneurysm wall

As shown in Figure 4 (A & B), the Von Mises stress distribution for the two models (intraluminal thrombus and porous intraluminal thrombus) was derived from static simulations of the peak systolic pressure for the top view of the wall.

Figures 5 (A & B) display the Von Mises stress distribution for the two models (intraluminal thrombus and porous intraluminal thrombus) derived from static simulations of the peak systolic pressure for the bottom view of the wall.



A: Solid ILT

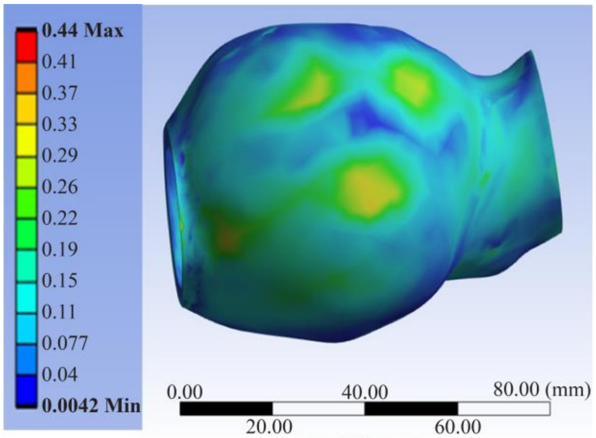


B: poroelastic ILT

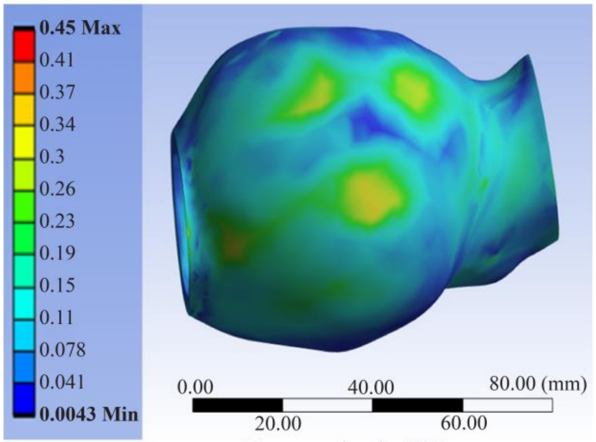
Fig. 4 Top view of abdominal aortic aneurysm wall

4. Discussion

In the present study findings, all figures indicate that the difference in the stress of the wall gained from the 3 conditions is insignificant (about 2.2%) based on the 2-models examined. The distribution of the stress on the wall and the position of the highest stress remain unchanged. Even when the pressure is applied directly on the wall, it appears like the intraluminal thrombus supports the wall. The results are consistent with those obtained by Polzer and Bursa [3], who employed porous and solid models for intraluminal thrombus, thus strengthening the present findings. In contrast, the outcomes of the two models concluded that when wall stress distribution is needed, intraluminal thrombus porosity can be altered. They reported that the poroelasticity of intraluminal thrombus did not change the wall stress. Using trans-thrombus theory, Polzer and Bursa [3] and Maier et al. [10] found that applying pressure directly underneath the intraluminal thrombus has only a small effect (about 03% difference) on wall stresses compared to applying pressure on the intraluminal thrombus. The findings of their study are also in good agreement with the present findings.



A: Solid ILT



B: poroelastic ILT

Fig. 5 Bottom view of abdominal aortic aneurysm wall

On the other hand, another study found that the porosity of intraluminal thrombus enhanced the wall stresses in comparison to non-porous ones [2]. They used porohyperelastic FEA models for both the intraluminal thrombus and the wall. They found that when porous intraluminal thrombus was compared to non-porous intraluminal thrombus, the peak maximum main wall stresses increased by as much as 81.0%. This looks quite high as if the intraluminal thrombus was totally eliminated, the stresses observed would be significantly higher between 20% and 60%. From a mechanical perspective, intraluminal thrombus was shown to play a protective role, and it was hypothesised that porosity would reduce this role without having a detrimental effect. Since intraluminal thrombus did not cause a significant pressure drop, as reported earlier [2]. Thus, it is possible that the high stresses they reported were caused by the use of a porous material for the wall that has a very low permeability. This leads to more deformation of the wall in comparison to a solid wall, which would yield higher stress.

In the current study, the emphasis of the investigation was limited to the role of intraluminal thrombus; the wall permeability was overlooked in the study as well as in the earlier studies [3, 10].

5. Conclusion

In conclusion, the intraluminal thrombus porosity could be overlooked if maximum wall stress is required. Thus, the influence of engaging porous media for intraluminal thrombus with the maximum value on the wall stress and distribution is unimportant.

Acknowledgements

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