Effect of thrombus on abdominal aortic aneurysm wall dilation and stress

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Aim. Our goal is to understand how a mural thrombus may influence the pressure transmitted to and the dilation experienced by the abdominal aortic aneurysm (AAA) wall.

Methods. Two intact AAAs with mural thrombus were removed from patients and pressurized to 100 mmHg. The pressure was measured using a micro-tip needle transducer inserted in the aneurysm wall and advanced through the thrombus. In 1 patient with AAA, similar measurements were made in vitro. Also, in vitro, in the two aneurysms the dilation as a function of pressure was measured using the markers on the surface before and after the thrombus was removed.

Results. Both, in vitro and in vivo, in the presence of the thrombus the pressure transmitted to the aneurysm wall was 91±10% of luminal pressure and at 6 mm from the wall it was 96±5%. The aneurysm dilated more in the pressure range of 0-40 mmHg (2.8%) than in the range of 40-100 mmHg (0.4-1.8%). Upon removal of the thrombus these dilations increased significantly to 4.15% and 0.9-3.3%, respectively. Overall, the strains (dilation) in the circumferential and longitudinal directions were similar before the thrombus was removed.

Conclusion. Even though the thrombus allows the transmission of luminal pressure to the aneurysm wall, it may prevent the aneurysm from rupture by diminishing the strain on the wall. Consistent with this, a mechanical model of the thrombus proposed is "a thrombus as a fibrous network adherent to the aneurysm wall".

KEY WORDS: Aneurysm, surgery - Aneurysm, ruptured - Thrombosis.

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Effective repair of an asymptomatic abdominal aortic aneurysm (AAA) is generally undertaken when the maximum diameter of the aneurysm exceeds 6 cm. Although most surgeons agree on this criterion, a similar consensus does not exist for smaller aneurysms. In this case, several factors influence their decision. While some aneurysms in the range of 4-7 cm diameter do rupture,1-2 their risk of rupture is largely unknown. Obviously, besides diameter some other factors are also considered to play an important role in the aneurysm rupture. The expansion rate,3 the ratio of the aneurysm diameter to the diameter of the aorta above, and the ratio of thrombus volume to aneurysm volume4 have been proposed as possible indicators for when to operate. Specific criteria related to these factors, however, have not been widely accepted.

Aneurysms are also being studied for the magnitude of mechanical stress present in their wall, a factor critical in determining whether the wall can sustain the pulsating pressure. Some studies described the stress distribution in the aneurysm wall5-8 and some work has also been reported on the material properties of aneurysmal tissue.9,10 The role of the mural thrombus in the aneurysm, however, remains undetermined. Since the thrombus is present in the cavity of the aneurysm, it is tempting to consider that the effective lumen
area, where the pressure is acting, may be decreased and consequently the pressure load on the aneurysm wall may be reduced. If so, this will lower the stress in the wall. Using such considerations, some studies have reported that the intraluminal thrombus significantly lowers the stress in the aneurysm wall.\textsuperscript{3, 6, 11} In contrast, a recent study has demonstrated that the thrombus within an aortic aneurysm fails to reduce transmission of pressure to the aneurysm wall.\textsuperscript{12} Even if the stress on the aneurysm wall is not reduced through this pathway, it is plausible that the thrombus may form fibrous connections, which may prevent the aneurysm from further dilation. Furthermore, the thrombus could also serve as a barrier for nutrients to reach the aortic wall making it prone to ischemia. Another study reported that \textit{in vivo}, the mural thrombus is more compliant than the aneurysm wall and suggested that it acts as a "cushion", protecting the more rigid aneurysm wall.\textsuperscript{15}

The purpose of the present study is to explore the effect of mural thrombus on the stress in the aneurysm wall. The study involved two sets of experiments: 1) pressure measurements \textit{in vitro} and \textit{in vivo} through the thrombus in AAA, and 2) expansion measurements \textit{in vitro} during pressurization of aneurysms before and after the thrombus was removed. Although the study reports the data on only a few aneurysms, we consider it to be very valuable because such data on whole aneurysms have not been available.
Materials and methods

Pressure transmission through the mural thrombus

Two symptomatic abdominal aortic aneurysms with mural thrombus were removed intact from 2 male patients, both age 70 (Figures 1, 2). The diameters of the aneurysms after removal were measured to be 5.3 cm (AAA 1) and 4.5 cm (AAA 2), respectively. The aneurysms were stored in saline at 4°C, and the experiments done within 48 hours of explant. The aneurysms were cannulated and filled with normal saline solution under 100 mmHg pressure, keeping the body of the AAA horizontal and free to expand in response to static pressurization and to pulsation (20–40 mmHg). The pressure transmission from the lumen through the thrombus was measured using a Millar micro-tip needle catheter pressure transducer inserted through the wall from the outside-inward and advanced through the thrombus in 2 mm steps (Figure 3). At each depth, the needle was fully rotated in 90° increments and pressure readings taken at each rotation. The readings were then averaged for that depth. Once the transducer tip had reached the lumen, it was withdrawn in 2 mm decrements and the pressure measured. The pressure transmission measurements were repeated at 2–4 sites in each of the anterior, lateral and posterior regions of the AAA, and through various thrombus thicknesses.

In vivo, in one patient, measurement of the pressure through the thrombus was done during surgery, just after exposure of the AAA. The patient was a 67-year-old male and the aneurysm was 5.7 cm in diameter. A 16-G angiocatheter modified with a side port and connected to a fluid pressure transducer (Transpac, Abbott Labs, Chicago, Ill.) was inserted through the aortic wall and advanced through the thickness of the thrombus in 2 mm increments. This procedure was repeated at one more site along the AAA length. The pressures inside the thrombus were averaged and compared to radial artery pressures as well as to the pressure within the lumen of the aneurysm.

In a different experiment, the mural thrombus was removed from aneurysm in a 60-year-old male patient, and placed inside a Dacron tube graft of matching size. The graft was cannulated and, as
create randomly distributed dots (Figure 4). The proximal end of the aneurysm was cannulated and the distal end was tied. A container of normal saline solution was connected to the cannula and was used to produce the desired hydrostatic pressure within the aneurysm (Figure 4). The pressure was measured with a transducer located at the same level as the horizontally placed aneurysm. The pressure was increased from 0 to 120 mmHg in 10-20 mmHg increments and then decreased in a similar manner. A video camera was used to record the expansion of the aneurysm as a function of pressure. A grid of known size was positioned on the aneurysm, allowing calibration of the distances on the aneurysm surface at all times. Usually the distance between the dots was around 3-5 mm and the magnification on TV was about 3-4 times.

By using still frames of the videotape, the distance between 2 dots oriented circumferentially and 2 dots oriented longitudinally was measured. The pressures were also recorded on the tape. The dots were chosen such that they remained in the field of the camera and closest to the objective throughout the experiment so as to minimize the distortion of the image. Then, the thrombus was carefully separated from the aneurysm wall, removed and the dilation experiments repeated.

Since the scatter of the experimental data was appreciable, the following procedure was implemented for the analysis: A) the measurements at a given site were obtained for 3 different pairs of dots in each direction; B) curves representing the distance d between 2 dots as a function of the luminal pressure P were plotted for all 3 pairs; C) each curve was then fitted to the following logarithmic function

\[ d = a \ln (P) + d_0 \]

where \( d_0 \) (the intercept on the \( d \) axis) represents the initial distance between the dots at a pressure of 1 mmHg. D) out of the 3 curves only the 2 that gave the best correlation factors (\( R^2 \) closest to 1) were used to determine \( d_0 \). The engineering strain \( \varepsilon \) was then calculated as \( \varepsilon = \frac{d - d_0}{d_0} \). The average curve for strain as a function of pressure was plotted using the arithmetic mean of the strains at a given pressure.

**AAA dilation under variation of the intraluminal pressure**

The two complete AAAs used in the previous pressure transmission experiments were also used in the dilation experiments. To determine the dilation of the aneurysm, the marker technique described below was used. In the anterior, lateral and posterior regions of the aneurysm, a finely ground potassium permanganate powder was sprinkled to
Results

Pressure transmission through the mural thrombus

The pressure transmission measurements obtained upon the insertion of the needle-catheter as well as upon its withdrawal, at one site of the aneurysm 1 are shown in Figure 5. At this location the thrombus was more than 8 mm thick. The pressure drop through the thrombus was at no time larger than 15%, and it was progressively less as the catheter approached the lumen. Since there was no significant difference in the results obtained between insertion and withdrawal, the pressure values at a given depth were averaged. The results obtained from multiple sites in each of the anterior, lateral and posterior regions of the aneurysm were further averaged (Figure 6). The maximum pressure reduction through the thrombus was 9±8% at 2 mm from the aortic wall, and it decreased to 4±3% at 6 mm. The pressure acting on the aneurysm wall was 92±6% of the luminal pressure.

In vivo, the pressure measurements showed a close match between the pressure inside the thrombus and that in the lumen (Figure 7). This was the case regardless of the depth and whether or not the measurements were made during insertion or withdrawal of the catheter. These results, however, varied with respiration and were averaged. When the patient had a systemic pressure of 124±68 mmHg, the pressure through the thrombus was measured to range from 125/55 to 127/55 mmHg. A systemic pressure of 128/65 mmHg was measured at another site within the thrombus to range from 138/55 to 143/58 mmHg. Hence, in a patient the complete transmission of pressure...
through the thrombus, measured in vivo, was in line with the results of previous in vitro experiments on aneurysms 1 and 2 and on the thrombus placed inside a tube graft. The combined results of all in vitro experiments are shown in Figure 8, where the maximum pressure drop through the thrombus was 12±10% at 2 mm from the aortic wall, and diminished to 4±5% at 6 mm. The pressure acting on the aortic wall was 91±10% of the luminal pressure.

**Aneurysm dilation under variation of the intraluminal pressure**

The intact aneurysms 1 and 2 were subjected to dilation measurements while the luminal pressure was changed between 0 and 120 mmHg. One set of representative results for the distance between 2 dots, oriented longitudinally, in the lateral region of aneurysm 1 is shown in Figure 9. With the thrombus present, the distance between the two markers increased slightly up to a pressure of 40 mmHg and then remained almost constant. After removal of the thrombus, the distance increased almost linearly up to a pressure of 60 mmHg, and then remained roughly unchanged. In both experiments, the data lent itself to a logarithmic curve fit. This method was used to extrapolate the distance between the two markers up to 0 pressure (y-axis). It was adopted because the data in the low pressure range were often not reliable. The extrapolated value as described in methods ($d_i$) was used to calculate engineering strains. The curves of the engineering strain as a function of pressure are shown for aneurysm 1 (Figure 10) and aneurysm 2 (Figure 11). All of the curves for the anterior, lateral and posterior regions and for both the circumferential and the longitudinal directions exhibited increased stiffness at higher pressures.

Comparison of strains with the thrombus present and removed was carried out for the two ranges of pressures: 0 to 40 mmHg and 40 to 100 mmHg (Table I). This separated the range of the large strains (0-40 mmHg) from that of the small strains (40-100 mmHg) which not only allowed better comparison but also predicted what may occur under systemic pressure.

For aneurysm 1, in the circumferential direction, the strains ranged from 4-7.8% for 0-40 mmHg pressure and only from 0.7-1.8% for 40-100 mmHg pressure in the presence of the thrombus (Table I). These strains ranged from 4.4-8% and 1.1-1.8%, respectively, when the thrombus was removed. Overall, in the circumferential direction, the presence of the thrombus did not significantly influence the strains. In the longitudinal direction, however, the results were different. For the pressure range of 0-40 mmHg the strains were in the range of 2.8-8% when the thrombus was present and higher. 3.6-11.4%, when the thrombus was removed. For the higher pressure range of 40-100
mmHg the strains were again lower (0.7-1.8%) when the thrombus was present and did not change much (0.9-2.5%) when the thrombus was removed.

In different regions of aneurysm 1, the findings were as follows (Table I, Figure 10). In the anterior region, in the circumferential direction, there was no significant difference in the strains with or with-
out the thrombus. The posterior region, however, showed an increase in strain to almost twice its value without the thrombus than with. The lateral region, contrary to expectations, exhibited almost the opposite behavior; the strains were less without the thrombus than with. In the longitudinal direction, both the anterior and the lateral regions showed larger strains without the thrombus than with. The strains in the posterior region, however, were slightly smaller without the thrombus than with.

For aneurysm 2, in the circumferential direction, the strains ranged from 2.4-5.6% for 0-40 mmHg pressure and only from 0.6-1.3% for 40-100 mmHg pressure when the thrombus was present (Table 1). These strains increased considerably when the thrombus was removed; 5.8-15.1% for 0-40 mmHg pressure and 1.4-3.3% for 40-100 mmHg pressure. In the longitudinal direction also, the strains were smaller when the thrombus was present and they increased when the thrombus was removed.

In different regions of aneurysm 2, the findings were as follows (Table I, Figure 11). In the anterior, lateral, and posterior regions, in the circumferential direction the strains were larger without the thrombus than with. Also, in the longitudinal direction in all of the three regions the strains were larger without the thrombus than with.

To describe the overall influence of the thrombus on the expansion of the aneurysms, the strains in all of the regions were further averaged (Figure 12). In aneurysm 1, the removal of the thrombus increased the strains in the longitudinal direction but not in the circumferential direction. For aneurysm 2, removal of the thrombus increased the strains in both the longitudinal and the circumferential directions. Furthermore, the thrombus influenced the strains more significantly in the lower pressure range (0-40 mmHg) than in the higher pressure range (40-100 mmHg).

It is also important to note that when the thrombus was present, the strains were nearly equal in both the circumferential and the longitudinal directions in all of the regions of the aneurysms, with only one exception, the lateral region of aneurysm 1 (Figures 10, 11). In other words, the mural thrombus distributed the strains homogenously throughout the aneurysm.

**Discussion**

Our study explored for the first time the pressure transmission through the mural thrombus as well as the expansion of the aneurysm wall with and without the thrombus in the same aneurysms. This was possible because of the availability of two complete aneurysms, both with mural thrombus.

The measurements of pressure through the mural thrombus revealed that the aneurysm wall is subjected to almost the whole (91%) of the intraluminal pressure. A similar finding was reported by...
Schurink et al., who showed that the mural thrombus does not reduce the mean or the pulse pressures near the aneurysm wall. This also agrees with Dobrin's view that the thrombus readily transmits the distending force of the pressure to the vessel wall. In our view, however, these findings do not simply indicate that the mural thrombus does not mitigate the risk of aneurysm rupture. Indeed, we observed that the presence of the thrombus was responsible for an overall marked reduction in the aneurysm expansion. The thrombus appeared to produce a reinforcing effect, which reduced the stretch on the aneurysm wall in almost all regions.

Mechanical model of the thrombus

Based on the above findings we propose a conceptual mechanical model of the thrombus, which is "the thrombus as a fibrous network adherent to the aneurysm wall" (Figure 13). Given the porous nature of the fibrous network while the thrombus transmits most of the luminal pressure to the aneurysm wall, it, however, reduces the dilation of the aneurysm under pressure, since the adherent fibrous network also has to stretch with the aneurysm. Because the thrombus may not be uniformly distributed inside the aneurysm, removing the thrombus may not increase the dilation uniformly, as seen in aneurysm 1 (Figure 10).

Obviously, the benefit of less dilation (strain) on the aortic wall is to reduce the wall stress. Inzoli et al., Mower et al., and Di Martino et al. already suggested that the mural thrombus lowers wall stress, however, the mechanism they described is not supported by our observations. In their studies, based on finite element models of aneurysms with or without (non-porous) thrombus, they proposed that the way the thrombus reduces the wall stress is by decreasing the diameter on which the pressure could act. Our experiments show that the magnitude of pressure exerted upon the aneurysm wall is almost equal to the luminal pressure.
To serve as an effective reinforcement, the thrombus has to be firmly adherent to the aneurysm wall, and this was the case in both aneurysms 1 and 2. In the presence of the thrombus, the dilation of the aneurysm was about the same in the circumferential and longitudinal directions, making the aneurysm more homogeneous and isotropic than the normal orthotropic aorta. Dobrin et al. stated that the mural thrombus does not have any significant retractive force; however, he based this on the observation that the thrombus in the aneurysm was generally easily removable at the operation.

Vorp et al. documented a cushioning effect of the intraluminal thrombus from in vivo measurements and reported that the average compliance of the aneurysm wall was about $4.0 \times 10^{-5}$ mmHg. In our in vitro measurements on aneurysms 1 and 2, the compliance of the aneurysm wall could be estimated from the circumferential strain produced for a pressure change from 60 to 100 mmHg. The wall compliance was about $3.0 \times 10^{-5}$ mmHg with the thrombus and about $6.3 \times 10^{-5}$ mmHg without the thrombus. These results are comparable.

Kushihashi et al. observed from CT images that the thickness of the mural thrombus was significantly smaller in ruptured than in non-ruptured aneurysms (9 mm vs 19 mm), which also suggests that the thrombus has a protective effect. Pillari et al. noted that larger (>7 cm) aneurysms contained less thrombus volume relative to wall diameter than smaller (5-7 cm) aneurysms. This suggests that the thrombus may reach a point of maximum relative volume and thus maximum protection for the aneurysm.

**Clinical significance of thrombus in aneurysm**

Because the strains are reduced by the presence of the thrombus, the stress in the aneurysm wall is also reduced. Thus, for two aneurysms of identical size, the one containing a thrombus has a lower wall stress and consequently is less likely to rupture compared to the other without the mural thrombus. If for some reason the thrombus undergoes lysis, then such an aneurysm will have two factors increasing the stress on its wall: it will have to bear the stress previously borne by the thrombus and it will also dilate immediately, thereby increasing the stress on it through the law of Laplace. Hence, lysis of the mural thrombus could be quite harmful to the patient.

Although the mechanical role of the thrombus seems to be positive, its long-term role on the underlying cells of the aortic wall is uncertain. Vorp et al. suggested that the thrombus could act as a barrier to the normal oxygen diffusion from the lumen to the inner layers of the aortic wall in which case the intima and media may become hypoxic, which may induce wall weakening.

**Conclusions**

The mural thrombus appears to protect the aneurysm by diminishing and homogenizing strain on the aneurysm wall. It appears to do so without restricting the pressure transmission through it. Consistent with this, a mechanical model of the thrombus is presented, which is "thrombus as a fibrous network adherent to the aneurysm wall".

**References**