A Personal note on a model for Angioplasty and Stent Insertion

Pedro V. Marcal,
MPACT Corporation, CA.
pedrovmarcal@gmail.com

ABSTRACT
The behavior of arteries near its exit is modeled with an axisymmetric thick cylinder. The end-effect is compensated for by extending its external radius. The material is assumed to be isotropic Mooney-Rivlin inelastic previously obtained by experiment. The model gives a first pass explanation for angioplasty for arteries with increasing Plaque.

Introduction.
A stent is a frequently used device by the medical practitioner to mitigate weakness in the arterial network. [1] estimates that 1.8 million stents are inserted each year in the U.S. It mostly accompanies an aged population. In broad terms, a weakness develops over a certain length of an artery. Plaque forms inside the artery as the body’s first defense against this weakness. In time this growth tends to restrict the flow of blood through the artery. In the current text, we restrict ourselves to consider only the arteries supplying blood to the heart. The procedure used to treat this arterial disease is known as coronary angioplasty. Appendix 1 gives a short summary of this procedure provided by the American Heart Association.

Let us consider the plaque as a symmetric and isotropic growth on the inside of the artery. This growth is partly pushed out by the blood flow. However some of it grows inwards and forms an occlusion to the flow. The occlusion grows in time and eventually causes an unacceptable blockage which results in blood starvation in the area where the artery feeds. The plaque formation is made worse by the presence of a diabetic type II disease. One area in which a stent is often placed is in the exit of arteries feeding the exterior of the heart. Occlusions form in the exit of the arteries and starve the outside of the heart of much needed blood. A cardio-vascular interventionist is called upon to remedy the situation. The procedure follows roughly along these lines. A guide wire is inserted in the groin area (or sometimes in the wrist). The catheter is advanced to the near exit region where the stent is to be inserted. A guide wire is then inserted in the catheter and guided past the artery exit. This guide wire is tracked by an X-Ray. A narrow balloon is pushed along the guide wire. The balloon is then inflated to deform both the plaque wall and the artery. The balloon inflation is enough to deform the plaque wall permanently so that the inner plaque wall allows a stent to be inserted and its wire wall similarly expanded by a balloon so that the stent prevents the arterial wall from collapsing over time. Typically, a pressure of between 8 to 16 atmospheres are applied. This procedure has been perfected so that cardio-vascular interventionists can perform such stent insertions about twenty times a week. On the whole, U.K. data suggests that 99% of such stent insertions are successful. In the 1% of failure, the patient is left with an option of another attempt at stent insertion accompanied by drilling out of some of the plaque so that stent insertion becomes possible. Now the risks of complications are higher. A surgical team stands by in case the drilling damages the artery. Again the U.K. data shows a 7% cases have some complication. The
The purpose of this note is to develop a simple model that will address the factors that should be considered during stent insertion.

Personal note. Recently the writer was diagnosed with 3 arterial occlusions. The major blockage was the so-called lower artery descending (LAD) supplying blood to the front of the heart. The first attempt at stent insertion failed at 12 atmospheres pressure. A second attempt at insertion failed at a pressure of 16 atmospheres followed by drilling. Finally the pressure was taken to 32 atmospheres as a final attempt followed by drilling. Fortunately this final attempt allowed the stent insertion. In the stent insertion procedure the patient is lightly sedated to a state of immobility. However the patient’s mind is still aware of the surrounding sound and the voices of the surgical team. The patient becomes like a spectator listening to a radio broadcast of the event. In the first attempt, there were five different attempts to inflate and insert a stent, Finally the surgeon decided to call a stop after about 1.5 hours. In the second attempt, the first pressure of 16 atmospheres followed by drilling and stent insertion failed. At this point it sounded much like the first event. The surgeon decided to try 32 atmospheres of pressure followed by drilling. This allowed the stent insertion. At the conclusion of the event the surgeon informed the writer that he had tried every trick in his experience to achieve the happy outcome.

**Review of Literature.**

In a series of experimental and theoretical work, Holzapfel et al [2-3] found the mechanical properties of arterial tissue and Plaques appropriate for analysis of the stent insertion process. Given the high stress loads concerned, the most important measurement is that of the inelastic behavior of the media material as shown in Fig. 1.

![Fig. 1 Media Inelastic Behavior](image-url)
The other important observation in [3] is the failure of the material at around 1500 kPa. Because of the high strains imposed by the ballooning, it was decided here to neglect all the elastic behavior including any spring-back. The constitutive model given in Fig. 1 may be approximated by an isotropic Mooney-Rivlin Material with $K_0=-200$ and $K_1=7007$.

The analysis of the Mooney Rivlin Material was carried out with the MPACT general purpose program [4].

**Theoretical Considerations.**

The geometry of the artery near an exit resembles that of a pipe insert in a flat plate. It is known that the extent of boundary conditions have a longer effect for rubbery materials compared to metals. This is shown by results on a long length of the artery assuming symmetry conditions that is shown on Fig. 2. The thick shell is constrained at one end and plane constrained against longitudinal movement on the other.

![Fig.2 Effect of end constraint, axisymmetric behavior, deformed shape.](image)

The result shows the boundary effect extending about half the length of the artery.
This is the basis for assuming that the behavior of the artery may be approximated by an axisymmetric flat plate in plane strain. The plate will have an internal radius of that of the artery. The external radius is chosen so as to allow the largest stresses to die off at the external radius. Through trial and error we found radii of 2 and 8 mm. respectively.

Fig. 3 shows the result of an analysis of our simplified model with 8 atmospheres of internal pressure.

The Fig. 3 shows the equivalent stress in the deformed state. A smaller grid in white shows the original geometry. The internal radius is found to expand from 2.0 to 4.6 mm. This stays almost constant independent of how much pressure is applied (from 8 to 32 atmospheres). The deformed internal radius namely 4.6-2.0=2.6 mm. is the basic inelastic deformation. This is the clearance that can be expected from a balloon application of 8 atmospheres on an artery.

Fig. 3 deformed and original mesh, sig_equiv, 8 atmospheres.

Fig. 4 shows the results for an internal pressure of 32 atmospheres.
Fig. 4 deformed mesh, sig_equiv., 32 atmospheres.

Fig. 4 shows a much higher stress in the interior radius. The equivalent stress of 6448.7 kPa cannot be maintained. [3] suggests that a maximum stress that can be supported by the material is around 1500 kPa. We assume that the inner radius will fracture from the inner radius to the radius where the equivalent stress becomes 1500 kPa. This then gives us the additional failed material (plaque) that can be removed by an application of internal pressure followed by drilling prior to stent insertion.

The following Table 1 summarizes the inelastic displacements that we can expect from our angioplasty procedures.

<table>
<thead>
<tr>
<th>Internal pressure, atmospheres</th>
<th>Basic inelastic deformation, mm.</th>
<th>Additional Fractured material, mm.</th>
<th>Max. stent radius with drilling, mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2.6</td>
<td>0</td>
<td>2.6</td>
</tr>
<tr>
<td>16</td>
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<td>0.34</td>
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</tr>
<tr>
<td>24</td>
<td>2.6</td>
<td>1.18</td>
<td>3.78</td>
</tr>
<tr>
<td>32</td>
<td>2.6</td>
<td>2.30</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Table 1. Available space for stent insertion due to Angioplasty.

The results obtained in Table 1 were derived from a simplified model. Yet they agree with the overall practice of pressures of between 8-16 atmospheres used for stent insertion. This in general produces a successful procedure with failure rates of 1%. Failure of the procedure is due to plaque formation. The plaque formation is a function of time. Taking the writer’s personal experience with 50 yrs. of diabetes II required a pressure of 32 atmospheres. Further research should produce a more accurate picture of plaque formation. In a first pass and following [3] the resistance to pressure was neglected because the fibers tend to be oriented in the longitudinal direction.
Table 1 provides a useful guide to the practitioner to estimate the pressure to be used in conjunction with a patient’s other medical history and test results. Further research should be carried out on the possibility of rupture at the higher pressures of either the artery material or the balloon material used.

**Conclusions**

A simplified model was developed for the inelastic deformation due to angioplasty. The model is based on the recognition that the end effect of the exit wall is significant for a long length of the artery.

[1] The simple model is based on an axisymmetric thick wall under internal pressure. The material is based on a Mooney Rivlin material defined by experiment in [2].

[2] The results from the simple model are presented in Table 1. Table 1 provides a first guide to the pressures that may be used in Angioplasty of the arteries providing blood to the external surface of the heart.

**References**


**Acknowledgements.**

It is a pleasure to acknowledge the care and information (most, while lightly sedated) provided by my Cardiologists, Dr. Roman Leibzon and Dr. Ravi H. Dave. I also owe my brother Dr. Jose M. Marcal for continuing advice and explanations.
What Is Coronary Angioplasty?

Your heart’s arteries can become blocked or narrowed from a buildup of cholesterol, cells or other substances (plaque). This can reduce blood flow to your heart and cause chest discomfort. Sometimes a blood clot can suddenly form or get worse and completely block blood flow, leading to a heart attack.

Angioplasty opens blocked arteries and restores normal blood flow to your heart muscle. It is not major surgery. It is done by threading a catheter (thin tube) through a small puncture in a leg or arm artery to the heart. The blocked artery is opened by inflating a tiny balloon in it.

Why do I need it?

People with blockages in their heart arteries may need angioplasty if they are having lots of discomfort in their chest, or if their blockages put them at risk of a heart attack or of dying.

How is it done?

1. A doctor numbs a spot on your groin or arm and inserts a small tube (catheter) into an artery.
2. The catheter is threaded through the arterial system until it gets into a coronary (heart) artery.
3. Watching on a special X-ray screen, the doctor moves the catheter into the artery. Next, a very thin wire is threaded through the catheter and across the blockage. Over this wire, a catheter with a thin, expandable balloon on the end is passed to the blockage.
4. The balloon is inflated. It pushes plaque to the side and stretches the artery open, so blood can flow more easily. This may be done more than once.
5. In many patients a collapsed wire mesh tube (stent) mounted on a special balloon, is moved over the wire to the blocked area.
6. As the balloon is inflated, it opens the stent against the artery walls. The stent locks in this position and helps keep the artery open.
7. The balloon and catheters are taken out. Now the artery has been opened, and your heart will get the blood it needs.

Does angioplasty hurt?

• No, angioplasty causes very little pain. The doctor will numb the place where the catheter will be