AML2506 ... Biomechanics and Flow Simulation

Day 09B

Pressure and Velocity Waves along the Aorta

Session Speaker
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• **Session Objectives**

  – At the end of this session the delegate would have understood:

    • Multiple Reflections in the arterial tree
    • Effect of Vessel Taper on Wave Reflection
    • Special flow cases like the the Aortic Arch, Stenoses and Aneurisms
Session Topics

- Multiple Reflections
- Effect of Vessel Taper on Wave Reflection
- Flow in the Aortic Arch
- Flow through the Vessel Stenoses
- Flow through the Vessel Aneurisms
Pressure and Velocity waves in large arteries (1)

Pressure in the left ventricle and ascending aorta of the dog. From Noble (1968).

See that the pressure in the aorta is slightly higher than in LV even before closure of the aortic valve, indicated by the dicrotic notch.
Simultaneous blood pressure measurements along the aorta in the dog. Distances are from the beginning of the descending aorta. From Olson (1968).

Calculate wave speed in the aorta: About 4 m/s.

We see a steepening of the wave and increase in the peak, but cross-sectional average value of pressure goes down (Not obvious, Only 4 mm in whole length.).
Pressure and velocity waves at different sites in the arteries in a dog. From McDonald (1974). Peak pressure, pressure amplitudes increase up to about 3 generations of branching, but peak and average velocity decrease. Pressure and velocity waves are not similar, indicating reflections.
Effect of Taper

Taper can be approximated as stepwise tubes of reducing diameter where reflections take place. See that in a tapered tube reflections and change in wave speed take place continuously.

Also if the taper is very gradual, the reflected energy is quite small.
Separation in a laminar flow B.L. at $Re = 20,000$. B.L. appears like a thin dark line at left and remains laminar till a dark line is seen.
Flow through a curved vessel

Notice the boundary layer growth at higher rate along the inside wall.

Secondary flows are shown schematically at D2.

Aorta is actually a three-dimensional artery and also has branches.

From: Atabek & Deshpande 1980
Flow through a curved vessel (Contd)

At the entrance of the aorta the velocity profile is uniform due to the converging shape of the entrance. It has been demonstrated to be true by actual measurements. [Station A].

As the flow proceeds into the arch, the flow gets skewed [Station B]. In the initial region, the boundary layer is thin and the flow in the core behaves like an inviscid flow. Hence applying the Bernoulli theorem along the streamlines:

$$\frac{1}{2} \rho V^2 + p_e = \text{constant.}$$

This constant is the same for all the streamlines.

$p_e$ is the so-called excess pressure ($= \text{Actual } p - \text{Hydrostatic } p$).

Due to the motion along a curved streamline of radius of curvature $R$ a radially outward pressure gradient $\rho V^2 / R$ results in higher $p_e$ and hence lower $V$ at the outer wall.
Stations C & D: As we move along the flow the viscous effects become predominant and the velocity near the centre increases due to the increase in boundary layer thickness and conservation of mass flux in each cross-section. The fluid at the core has higher inertia due to higher velocity and hence tends to move towards the outer wall, setting in secondary flows as shown at D2 in the figure. Hence the streamlines are helical.

If we cannot maintain the curved part of the tube and the flow enters a straight part of the tube the secondary flows decay gradually due to the viscous effects.

Because of the secondary flows, there is higher exchange of momentum in the transverse direction and the entrance region gets shorter and there is also a higher pressure drop.
Flow through the Aorta - 1

The wall shear stress $\tau_w$ is higher in the entrance region due to the thinner boundary layer. In a curved tube $\tau_w$ is higher along the outside wall than the inside wall, except close to the entrance. See section B in the figure.

Flow in the aortic arch is much more complicated than in the rigid model just discussed because:

- Flow in that aorta is pulsatile.
- Entrance conditions are more complicated due to the aortic valve.
- The aortic wall is not rigid but is elastic.
- There are branches (Brachiocephalic and left subclavian) and also the aorta is not in one plane (twisted). The effect of branches is to skim off the high momentum flow along the outside wall and thus reducing the strength of secondary flows.
Flow through the Aorta - 2

Existence of secondary flows has been verified experimentally by Flaherty et al (1972).

The endothelial nuclei have a tendency to orient their major axes along the flow direction. This was proved separately by controlled experiments on the canine descending aorta. In about 10 days the nuclei could adjust to the changed flow.

In the aortic arch the nuclei were found to be oriented nonaxially. The patterns on the dorsal and ventral walls were mirror images of each other giving the appearance of a double spiral. See the figure.

Just distal to the branches, the double spiral pattern was less marked, confirming a reduction in the strength of the secondary flows.
Flow through the Aorta - 3

Endothelial nuclear pattern in the canine aorta.

Φ is the nuclear orientation angle w.r.t. the longitudinal axis of the aorta.

Note: The Pattern shown here is representative and is prepared from measured data.

From: Flaherty et al 1972.
Photomicrograph of the Endothelial nuclear pattern. (a) Normal in control area just downstream from turned area in canine MDTA. Flow is left to right. Contd)
(b) Day 0: Nuclei in turned segment are oriented circumferentially. The scale bar is 25 μm. (Contd)
(c) Day 3: Nuclei in turned segment are still oriented circumferentially. Regrouping in C- and L-shaped forms is seen. (Contd)
(d) Day 3: Nuclei in another turned segment. Rounded forms with some longitudinal orientation is seen. [Cf with frame (c).] (Contd)
(e) Day 10: Endothelial Nuclei are longitudinally turned along the flow but hypercellular.
(f) Day 70: Uniform endothelial Nuclei pattern oriented back longitudinally along the flow. [Cf with frames (c and e)]. From: Flaherty et al 1972.
Flow through Branches

The vascular system needs branches to distribute the blood into various parts. Most branches are unsymmetrical, i.e. not Y-branches.

In our earlier study we have considered reflections at a branch. In those studies flow was idealised. We see here from a different perspective. The real flow is viscous, the branch geometry is complicated and the disturbances and deflections are not necessarily small.
Flow through Branches (Contd)

Steady Flow through a Rigid Model

- It is instructive to study such an idealized model, even though the actual case is so complicated.

- Dye injection studies (Roach 1977; Ferguson & Roach 1972) were made in glass models. Injection along the axis impinged on the apex and bifurcated into the two arteries. Dye stream in the boundary layer showed separation at the outer wall near the bend and reattachment further downstream.

- As the flow rate increased, a helical pattern developed, particularly in the wide angle bifurcation.

- A further increase in flow resulted in turbulence being localized to the upstream portion of the bifurcation leg. A still further increase in flow rate resulted in turbulence throughout the bifurcation leg.

- $Re(\text{crit})$ for turbulence to develop is much smaller than for a straight tube [2,300 steady flow, 2,000 pulsatile flow].
Flow through Branches (Contd)
Pulsatile Flow in a Distensible Model

- The results from Ling et al (1968) were obtained in a model bifurcation made from silicone rubber GE RTV-108.
- Diameter of main branch = 6.8 mm, side branch = 4.2 mm.
- Wall thickness = 0.7 mm.
- A heart pump delivered 5.1 ml / stroke and set at 120 stroke/min.
- The flow through the side branch = 1.4 ml / stroke.
- Velocity measurements were made using a hot film anemometer.
Flow through Branches (Contd)
Pulsatile Flow in a Distensible Model (Contd)

$w_0 = \text{Local max vel} (= 110, 100, 94, 68 \& 77 \text{ cm/sec at stations A, B, C, D & E})$. From Ling et al (1968)
Flow through Branches (Contd)
Pulsatile Flow in a Distensible Model (Contd)

The results from Ling et al (1968) show that:

- Velocity profiles at station A ($w_m = 110$ cm / sec) are skewed. Notice how the skew side changes during the deceleration phase.

- Velocity profiles at station B ($w_m = 100$ cm / sec) are skewed and are similar to those at station A. During the high velocity period, the gradients are high at the inner wall leading to high $\tau_w = 260$ dyn / cm$^2$.

- At station C (4 cm distal to B) entrance effects are still visible. They were absent at a point 10 cm distal to B & beyond (Not shown).

- At station D in the side branch ($w_m = 68$ cm / sec) velocity is higher near the lip with $\tau_w = 260$ dyn / cm$^2$.

- At station E (2.3 cm distal to D) entrance effects have disappeared, giving blunt symmetrical profiles. This is due to lower $Re$. 
Flow through Branches (Contd)

- The branch has a tendency to skim the boundary layer of the parent artery and to divert the high momentum flow from the centre toward the inner boundary.

- The flow entering the branch has to change the direction. This leads to higher wall shear near the inside wall or the lip of the flow divider. There is a tendency to generate secondary flows due to the curvature of the streamlines.

- The secondary flows lead to better mixing and shorter entrance length.
Flow through Arterial Stenosis (1)

❖ Arterial stenosis occurs in man as a coarctation of the aorta or as discrete stenosis in its branches. The latter can also occur in the major branches of the pulmonary artery.

❖ The flow field gets affected both locally and distally.

❖ Local wall shear stress increases. This may damage the endothelial layer and also cause hemolysis (damage to RBC).

❖ Because of high velocity in the neighbourhood of the throat pressure decreases to a low value. Recall Bernoulli equation, even though it is not exactly applicable.
Schematic diagram of flow through an arterial stenosis. Streamlines are shown in the bottom half and velocity profiles in the top half at various locations. S = separation point; R = reattachment point.
Stenosis with 56 % area reduction. Locations of Separation and Reattachment points along $Z$. From: Deshpande, Giddens & Mabon (1976).
Stenosis with 56 % area reduction. Centreline velocity for three values of $Re$ along $Z$. From: Deshpande, Giddens & Mabon (1976).
Stenosis with 56 % area reduction. Pressure distribution along $Z$ compared with that for Poiseuille flow. From: Deshpande, Giddens & Mabon (1976).
Flow through Arterial Stenosis (6)

Stenosis with 56 % area reduction. Wall shear stress plotted for four values of $Re$ along $Z$. From: Deshpande, Giddens & Mabon (1976).
Stenotic flow and flow separation

Flow is simulated assuming it to be steady & axisymmetric.

Fluid is incompressible & viscous.

Separation length grows with the Reynolds No.

Fluid mechanics of arterial disease

The formation of the plaques is predominantly in low shear stress areas.
From Thubrikar & Robicsek (1995).
Review

• Causes for Multiple Reflections are identified.
• Effect of Vessel Taper on Wave Reflection is seen.
• Flow in the Aortic Arch is studied.
• Flow through the Vessel Stenoses is studied.
• Flow through the Vessel Aneurisms is studied.
Thank you