6. S.Iida et al; NASDA Large Space Chamber, 12th ISSTS Tokyo pp739-744 1977
7. private communication by Prof.M.Hinada, ISAS University of Tokyo

SUPPLEMENTARY REFERENCES

The supplementary references for these topics are listed below. These are chosen from the standard text books or monographs and some papers significant in the corresponding field.

8. R.H.Noris et al, ed; Heat Transfer Data Book, General Electric Co. 1977
9. E.M.Sparrow & R.D.Cess; Radiation Heat Transfer, Brooks/Cole Publ. 1970
10. A.M.Smith ed; Thermophysics of Spacecraft and Outer Planetary Entry Probes, Prog. Aero. Astro. 56 1977
11. L.S.Fletcher ed; Aerodynamic Heating and Thermal Protection Systems, & Heat Transfer and Thermal Control Systems, Prog. Astro.Aero. 59 & 60 1978
12. R.Viskanta ed; Outer Planet Entry Heating and Thermal Protection & Thermophysics and Thermal Control, Prog. Astro.Aero. 64 & 65 1979
13. G.A.Bird; Molecular Gasdynamics, Oxford UP 1976
14. L.Steg ed; Materials Sciences in Space with Application to Space Processing, Prog. Astro. Aero. 52 1977
15. W.A.Campbell,Jr. et al; Outgassing Data for Spacecaft Materials, NASA Ref. Pub. 1061 1980
16. J.B.Stephens; Space Molecular Sink Simulator Facility Design, J.Spacecraft 3 pp844-848 1966
17. J.C.Scialdon; Self-Contamination and Environment of an Orbiting Satellite, J.Vacuum Sci. Tech. 9 pp1007-1015 1971
18. D.A.Wallace; Use of the Quarz Crystal Microbalance for Outgassing and Optical Contamination Measurements, J.Vacuum Sci.Tech. 9 pp462-466 1972
19. Space Simulation, NASA SP-298, prepared by Goddard Space Flight Center 1972

HYDRODYNAMIC STUDY ON VASCULAR LESION

Mitutosi KAWAGUTI and Akiko HAMANO

Dept. of Physics, Keio University
Hiyoshi, Yokohama, JAPAN

1.0 INTRODUCTION

It is well known that vascular lesion appears usually downstream of a constricted portion (stenosis), in the neighbourhood of a branch, in the region where the curvature of an artery is very large as in the aortic arch, and so on. But, its origin has not been conclusively elucidated, in spite of many theoretical and experimental works/1/-/3/.

The present series of numerical study is aimed at searching for the origin of vascular lesion from the hydrodynamic point of view. In §2, numerical study on the viscous flow in a constricted channel is given as a two-dimensional model of blood flow in a constricted vessel. Steady and pulsatile flows of a viscous fluid in a channel with a branch are numerically studied in §3.

2.0 VISCOUS FLOW IN A CONSTRICTED CHANNEL

2.1 When there appears a constriction in artery for some reason or other, the region downstream of constriction often starts to swell, and it is called "post-stenotic dilatation" (PSD) and one of main disease in artery. Concerning the origin of PSD, there have been many theories:

(1) stasis in standing vortex downstream of constriction (Fox and Hugh/4/, Caro/5/),
(2) pressure variation (Holman/6/),
(3) turbulence(Roach/7/),
(4) cavitation(Rodbard et al/8/),
(5) shearing stress(Roach/7/, Fry/9/),

but its origin has not been clearly explained. It is one of paradoxes from the hydrodynamic point of view.

In order to search for the origin of PSD from the hydrodynamic point of view, the authors studied numerically steady flows and pulsatile flows of a viscous fluid through a channel with a rectangular hump as shown in Fig.1, as a two-dimensional model of constricted artery.

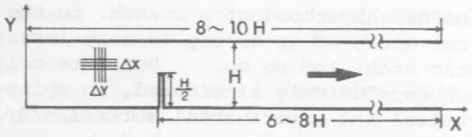

Fig.1 Model(constricted channel).

2.2 Steady Flows

In terms of stream function ψ and vorticity ω, the equations of motion for the unsteady flows of a Newtonian fluid with a density ρ and a viscosity η can be written in non-dimensional form as

$$\frac{\partial\omega}{\partial t} = \frac{\partial\psi}{\partial x}\frac{\partial\omega}{\partial y} - \frac{\partial\psi}{\partial y}\frac{\partial\omega}{\partial x} + \frac{1}{R}\nabla^2\omega \qquad (1)$$

where

$$\omega = -\nabla^2\psi \qquad (2)$$

and

$$R = \rho HU/\eta \qquad (3)$$

U and H being the width of the channel and the mean fluid velocity in the channel, respectively.

For steady flows, following boundary conditions were used:

(i) The velocity vanishes on the wall (Wall is assumed to be rigid).

(ii) The stream function and vorticity far upstream and far downstream are given from the Poiseuille flow.

Calculation of steady flows at the Reynolds number of 32, 64, and 96 was obtained as a limit of unsteady flow.

It was shown that the length of the standing vortex downstream of the hump is roughly proportional to the Reynolds number.

2.3 Pulsatile Flows/10/

For the pulsatile flows, we have solved the equations of motion for the cases: Reynolds number of 32, and non-dimensional period T of 0.5, 1, 3, and 10. The boundary conditions far upstream and far downstream (ii) in steady flows must be replaced with

(ii') The stream function and vorticity far upstream and far downstream are given from the pulsatile flow in a straight channel without a constriction, with a pressure gradient

$$\partial p/\partial x = -[A + B\cos(2\pi t/T)] \qquad (4)$$

(two-dimensional Womersley's flow).

The series of calculations were made: (a) The cases where $A = B$ in (4) and,(b) The cases where the change of flow rate during a period is half of the average flow rate Q_{mean} (i.e. $Q_{max} = 1.5\,Q_{mean}$).

In Fig.2, is shown the amplitude of shearing stress for the cases (b) during one period on the wall downstream of hump. The amplitude shows quite apparent maximum (about two-fold of that for the other places) in the neighbourhood of the re-

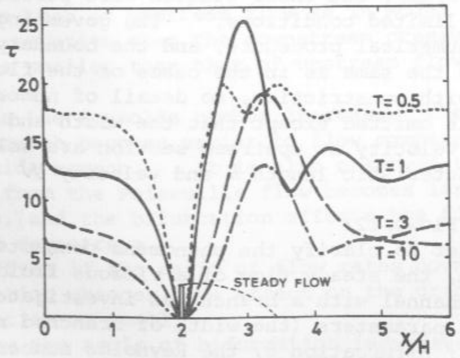

Fig.2 Amplitude of shearing stress τ on the wall.

attaching point of the streamline separated from the hump for the steady flow.

From the numerical calculation shown above, we can conclude as follows:

In the neighbourhood of the reattaching point of the separated streamline for the steady flow, total variation of shearing stress on the wall is very large and the pressure shows locally weak maximum there. Since the large temporal variation of shearing stress may lead to fatigue and breakdown of the wall of the channel (that is, which corresponds to endothelium of artery), it is strongly suggested that the hydrodynamic cause of endothelial lesion of artery and post-stenotic dilatation can be found in the large temporal variation of shearing stress behind a constricted portion of artery. Local maximum of the pressure there may be seen as secondary factor for the post-stenotic dilatation.

3.0 VISCOUS FLOW IN A CHANNEL WITH A BRANCH

3.1 Steady flows and pulsatile flows of a viscous fluid in a channel with a branch were studied as a two-dimensional model of blood flow in an artery with a branch, by solving numerically the Navier-Stokes equation.

The same problem was studied by some authors/11/, but their studies were performed under very limited conditions. The governing equation, numerical procedure, and the boundary conditions are the same as in the cases of the flow in a channel with constriction, so detail of numerical procedure is omitted except that the width and the mean fluid velocity at upstream section are selected as characteristic length H and velocity U.

3.2 Steady Flows/12/

In order to clarify the phenomena connected with bifurcation, the steady flow of a viscous fluid through a channel with a branch was investigated for various parameters (the width of branched region, the angle of bifurcation θ, the Reynolds number R, the ratio of flow rates downstream of bifurcation ψ_{sep}).

Five models shown in Fig.3 were studied. For each model, three cases were investigated:

(1) $R = 32$, $\psi_{sep} = 0.5$
(2) $R = 32$, $\psi_{sep} = 0.35$
(3) $R = 64$, $\psi_{sep} = 0.5$

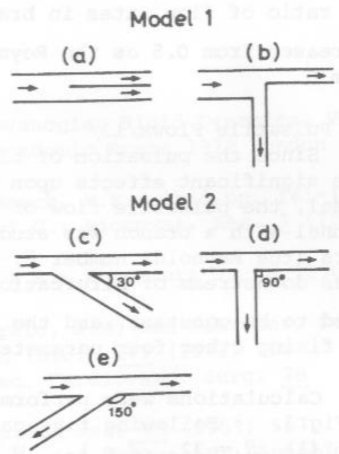

Fig.3 Models for channel with a branch.

Calculation to determine the ratio of flow rates downstream of bifurcation ψ_{sep} when the length of branched region is finite, was performed for the case (d), $R = 0 \sim 96$, and the length of branched region is five times of the channel width, from the condition that the pressure of both downstream ends is taken to be the same.

Main conclusion obtained from our numerical work is as follows:

i) The drag increase due to bifurcation is positive, when the downstream pressure gradient is larger than that of upstream flow as in Model 1. But, it is negative when the downstream pressure gradient is smaller than that of upstream flow as in Model 2.

ii) As the Reynolds number increases, the straight branch becomes easier to flow compared with the side branch. It is also observed that deviation from the Poiseuille flow becomes larger as a whole, and the bifurcation affects the flow fairly far downstream.

iii) Even if the ratio of flow rates downstream of bifurcation changes, the effect on the drag due to bifurcation is small.

iv) As the angle of bifurcation increases, the drag of the side branch increases. This tendency becomes marked when the Reynolds number is large.

v) When the length of branched region is finite, the ratio of flow rates in branched section ψ_{sep} decreases from 0.5 as the Reynolds number increases from 0.

3.3 Pulsatile Flows/13/

Since the pulsation of blood flow seems to have more significant effects upon the wall of blood vessel, the pulsatile flow of a viscous fluid in a channel with a branch was studied for three parameters (the Reynolds number R, the ratio of flow rates downstream of bifurcation ψ_{sep} which was assumed to be constant, and the period of oscillation T), fixing other four parameters.

Calculations were performed only for model (d) in Fig.3. Following five cases were studied:

(1) $R = 32$, $T = 1$, $\psi_{sep} = 0.5$
(2) $R = 32$, $T = 1$, $\psi_{sep} = 0.35$
(3) $R = 64$, $T = 1$, $\psi_{sep} = 0.5$
(4) $R = 64$, $T = 3$, $\psi_{sep} = 0.5$
(5) $R = 64$, $T = 10$, $\psi_{sep} = 0.5$.

Main conclusion obtained from our numerical work is as follows:

i) As in the case of pulsatile flow in a constricted channel studied in §2, amplitude of shearing stress near the point upon which the separated streamline reattaches in steady flow becomes large, when the period is large.

ii) For the longer period, the amplitude of shearing stress near the bifurcating corner is fairly large.

iii) Effect of bifurcation increases as the Reynolds number increases.

iv) Change of ratio of flow rates has little qualitative effect upon the flow.

v) For the pulsatile flow in bifurcating channel, it is sufficient to consider as far as the second higher-mode, when the pressure upstream changes in a sinusoidal form.

4.0 REFERENCES

/1/ Roach, M.R.: "Cardiovascular Fluid Dynamics, Vol. 2" ed. Bergel, D.H., Academic Press 1972 London and N. Y. pp. 111-139.
/2/ Ferguson, G.G. and Roach, M.R.: ibid.pp. 141-156.
/3/ Lee, J.S. and Fung, Y.C.: Microvas. Res. 3 (1971) 272.
/4/ Fox, J.A. and Hugh, A.E.: Br. Heart J. 28 (1966) 388.
/5/ Caro, C.G., Fitz-Gerald, J.M. and Schroter, R.C.: Proc. Roy. Soc. London (Biol) 177 (1971) 109.
/6/ Holman, E.: J. Thorac. Cardiovasc. Surg. 28 (1954) 109.
/7/ Roach, M.R.: Circulation Res. 13 (1963) 537.
/8/ Rodbard, S., Ikeda, K. and Montes, M.: Angiology 18 (1967) 349.
/9/ Fry, D.L.: Circulation 39 suppl. 4 (1969) 38.
/10/ Kawaguti, M. and Hamano, A.: Proc. 10th International Congress of Angiology (Tokyo, 1976) 393.
/11/ O'Brien, V., Ehrlich, L.W. and Friedman, M.H.: J. F. M. 75 (1976) 315.
/12/ Kawaguti, M. and Hamano, A.: J. Phys. Soc. Jpn. 46 (1979) 1360.
/13/ Kawaguti, M. and Hamano, A.: J. Phys. Soc. Jpn. 49 (1980) 817.