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'Effect of Atherosclerosis on Cerebral Blood Flow -- In vitro Studies'

by

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled 'Effect of Atherosclerosis on Cerebral Blood Flow -- In vitro Studies' submitted by Waqar-ul-Haque in partial fulfilment of the requirements for the degree of Master of Science.

DEDICATED TO MY PARENTS

ABSTRACT

An elastic model of the main branches of the arterial system has been developed and a set-up designed to simulate the pumping action of the heart under normal and abnormal conditions. Natural flow and velocity profiles together with the normal cardiac output (with capability of variable output) are the features of the system. A normal flow distribution was first obtained in the main branches of the arterial tree in accordance with the available information and was then used as reference. The geometry of the model and the corresponding flow distribution used covers over 70 percent of the normal human beings.

Atherosclerosis was then represented by introducing blockages of known cross-section at the specific sites of predilection. Individual artery stenosis and combinations were studied to determine the effect of one or more diseased arteries on the blood flow distribution. The adversity of the disease was simulated by reduction in cross-section to the degree of complete blocking. Cerebral blood flow was emphasized in order to determine the feasibility of a surgery in the event of a diseased artery which may be directly or indirectly responsible for supplying blood to the brain. The information obtained can be used to determine the requirement of a by-pass if a surgical

treatment is recommended. Angiographic information is required to use the results given in Appendix A. These results also form the ground for mathematical/computer modelling of the system so that there is more flexibility in the interpretation of the results.

The present work may be considered as an extension to the pilot project (Rodkiewicz et al., 1979) but the experimental parameters involved and the experimental conditions developed in the present research happen to be more 'natural' and convincing for a direct application of the results to the human beings. The present analysis has also been extended to more branches in the arterial system.

ACKNOWLEDGEMENTS

I wish to extend my appreciation to Dr C M Rodkiewicz whose ever available guidance was a great source of inspiration during the course of research. The confidence he reposed went a long way in inculcating a driving spirit of zeal and hard work. I feel that work and not words are the most befitting way of expressing my appreciation to his dedicated efforts and keen interest in the project.

To Dr J Centkowski, I express my warmest thanks for his interest and assistance in the fabrication phase of the experimental set-up by applying his experience in the field of Fluid Dynamics.

Thanks are also extended to the Natural Sciences and Engineering Research Council of Canada for the grant under NSERC - A4198 which were instrumental in the completion of the thesis.

Waqar ul Haque

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LIST OF ABBREVIATIONS

BRAC .. Brachiocephalic Artery

CORO .. Coronary Arteries

ILIA .. Iliacs

LCCA .. Left Common Carotid

LEXC .. Left External Carotid

LINC .. Left Internal Carotid

LSCB .. Left Subclavian (at emanation from the arch)

LSCL .. Left Subclavian (after giving off LVER)

LVER .. Left Vertebral

RCCA .. Right Common Carotid

RENS .. Renals

REXC .. Right External Carotid

RINC .. Right Internal Carotid

RSCB .. Right Subclavian (at branching from BRAC)

RSCL .. Right Subclavian (after giving off RVER)

RVER .. Right Vertebral

TFBR .. Flow to the Brain

TFLO .. Total Flow

CHAPTER 1

INTRODUCTION

Heart and artery diseases currently account for more than 50 percent of the total deaths in North America, occuring most frequently in individuals who are in excess of 40 years of age. This is very much true for the other parts of the world, as well. Through many epidemiological studies, it is well established that atherosclerosis and arteriosclerosis are important contributing factors in over 80% of these deaths. The percentage of all cardiovascular diseases is increasing everyday.

Atherosclerosis had been an important topic in research on cardiovascular diseases over the last decade or so. But, unfortunately, most of the research carried out in this area concentrated on the causes of the disease and the biological and pathological changes associated with its development; not much work has been done to determine the effects of atherosclerosis on the blood mass flow distribution in the arterial system when one or more of the branches are affected by it.

As regards the cause, it can be concisely said: "Atherosclerosis is a price we pay for blood flow as a requirement of life" (Texon,1980). At this point it should

be noted that while the development of atherosclerosis must depend upon the operation of its primary etiologic factor (local diminution in lateral pressure produced at sites of predilection by the effects of flowing blood) the rate of development and severity of the disease may be modified by biological factors. It is here that genetic tissue differences in reactive or reparative response to injury at the cellular level may determine the nature and degree of atherosclerotic change in each individual (Texon, 1980).

Atherosclerosis is characterized by an accumulation of soft masses of fatty materials, particularly cholestrol, beneath the inner lining of arteries (Hole, 1978). These deposits develop protruding into the lumens of the vessel and interfering with the blood flow. These so called 'plaques' can develop to the degree of partially or completely blocking off the flow thereby causing serious damage to the organs supplied by that artery. As an example, if the cerebral[1] blood flow is reduced to 50% or lower than the normal flow, a permanent damage to the brain becomes inevitable.

Atherosclerosis can also develop into arteriosclerosis when the affected arteries undergo degenerative changes during which they lose their elasticity, become hardened and are susceptible to rupture under the force of the blood pressure (Hole, 1978).

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[1]The term 'cerebral', for now and all other occurences in the text, would refer to the whole brain.

The effect of atherosclerotic lesions on the blood mass flow distribution was first studied by Rodkiewicz et al. (1979) when a rigid model of the aortic arch, with the primary branches, was used. The experiments were carried out for a steady flow and a set of blockage combinations was tested. The Reynolds number, at entrance to the aorta, was kept around 1300 during the experiments. The results obtained, however, were limited in the sense that the experimental variables were not close enough for direct application to the human beings.

The present analysis takes into consideration the actual features of the human blood circulation. An elastic model was developed and used; it had a property of dilating under pressure together with a geometry that represents over 70% of the human beings (McDonald and Anson, 1940; DeGaris et al., 1933). Prosthetic heart valves were used and a pulsatile flow was maintained with a flow profile similar to that actually produced by a human heart. More branches were included in the model with emphasis on arteries responsible for the cerebral blood flow. The working fluid was an acqueous-glycerol mixture that had a viscosity and density same as that of the blood. In this way, the results found from this set-up , as given in Appendix A, can be applied directly to the patients suffering from atherosclerosis.

The aim of the project was the study of cerebral blood flow at different stages of atherosclerosis in the arteries which are directly or indirectly responsible for supplying

blood to the brain. These include the vertebrals, internal carotids, common carotids, brachiocephalic and the subclavians. Specially shaped blockages were used at specific sites to represent the atherosclerotic lesions. The adversity of the disease was simulated by putting blockages with smaller, known cross-sectional area. Though the study was concentrated on the cerebral blood flow, the model was fabricated in such a way that the analysis could easily be extended to the lower region, for example, the renals or the iliacs which are also prone to atherosclerosis.

The experimental results obtained can be used for mathematical modelling of the system so that a handy computer package is prepared to provide assistance to the surgeons. The only input required for obtaining the information regarding the flow distribution in the whole system will be the angiographic data of the diseased artery. In order to have a more comprehensive program, the experiments may be repeated for hearts with a lower and a higher output than normal together with varying pulse rates. The existing apparatus was designed to incorporate both these capabilities. The only change required, for the former, is the replacement of the piston and the cylinder and, for the latter, is to adjust the gear train. In this case, three input parameters, namely, the angiographic data of the affected artery, the cardiac output and pulse rate will be required to obtain the information from the computer

package.

The results presented in Appendix A were obtained for pulse rates of 50, 70 and 90 with distribution at 70 beats/minute taken as the reference. The corresponding reference cardiac output was approximately 5.7 litres/minute i.e. about 80 ml per beat.

The first part of the experiments consisted of obtaining the right rates of flow through each branch so that a normal reference condition was set. This distribution was obtained from a number of sources as given in Chapter 3 and was accomplished through the regulating valves at the outlet from each branch. The results were reproduced a few times before sealing the valves at the reference position.

Atherosclerosis was then simulated in different arteries by replacing the connectors with blockages of known cross-section at the specific sites previously determined. The flow distribution for each set of blockages was recorded and analysed. In all, 66 different combinations, as determined by surgeons, were simulated and flow distribution was recorded for the three different Reynolds numbers at 50, 70 and 90 beats per minute.

CHAPTER 2

THE OPERATIONAL SET-UP

The system used for the complete study and data collection comprised of three main parts:

a) pulsatile unit,

b) reservoir containing the model, and

c) measuring arrangement.

These three parts were connected together to work as a single unit.

The layout of the system is shown in Fig 2.1. Plates 1 and 2 show the laboratory arrangement of the same.

2.1 Pulsatile Unit

The pulsatile unit was designed to simulate the pumping action of the heart and was the driving source for the whole system. The unit was powered by a 115 volt, single phase, 0.2 hp, a.c. motor having a shaft speed of 3450 rpm. A standard speed reduction gear box reduced the speed to 480 rpm at the output shaft and a further train of gears (Fig 2.2a, 2.2b and 2.2c) left provision to reduce the speed within a feasible range corresponding to the conditions of depression and excitement of an individual or to variations of pulse rate from person to person. The trains used for

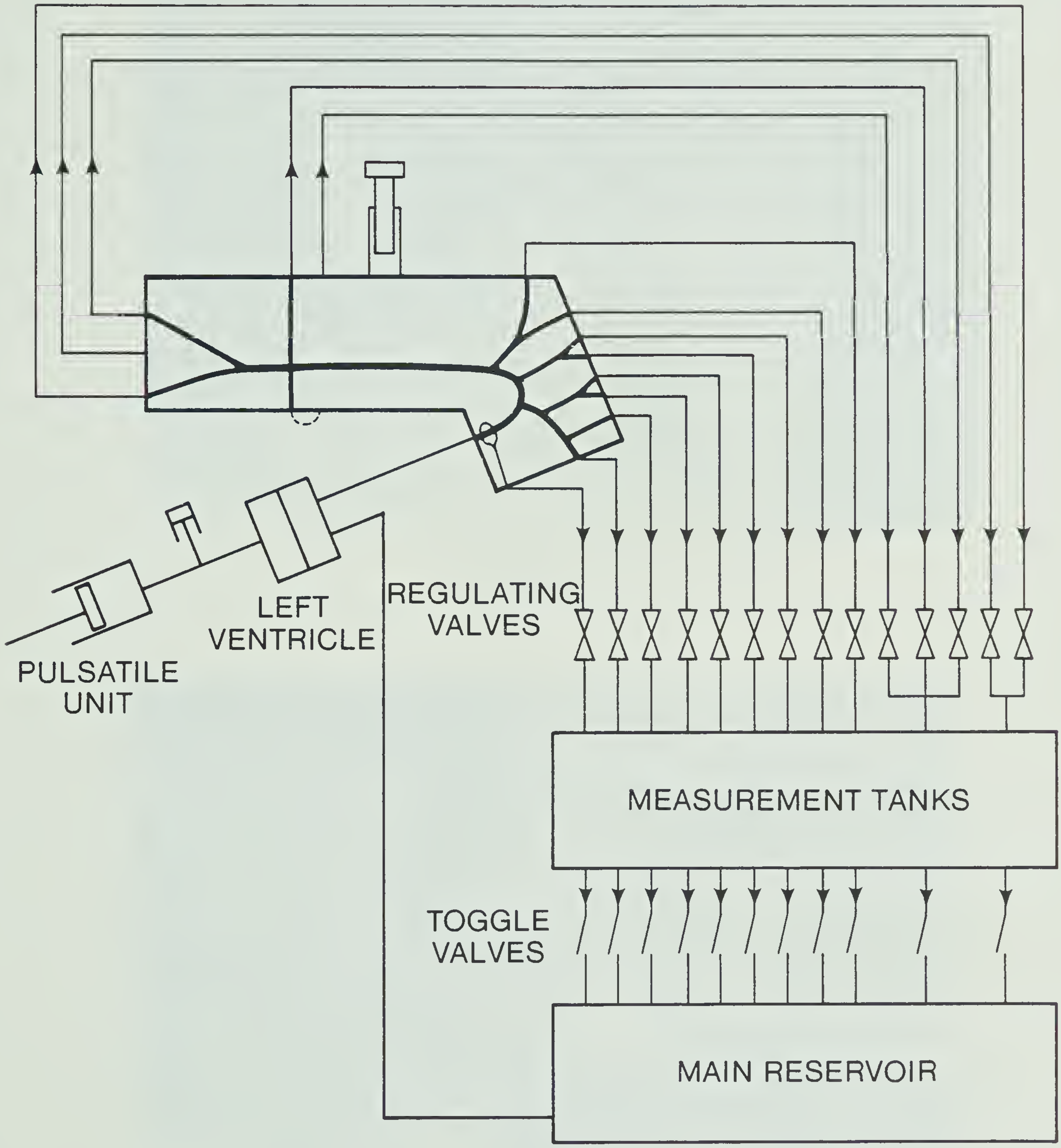


FIG 2.1 LAYOUT OF THE SYSTEM

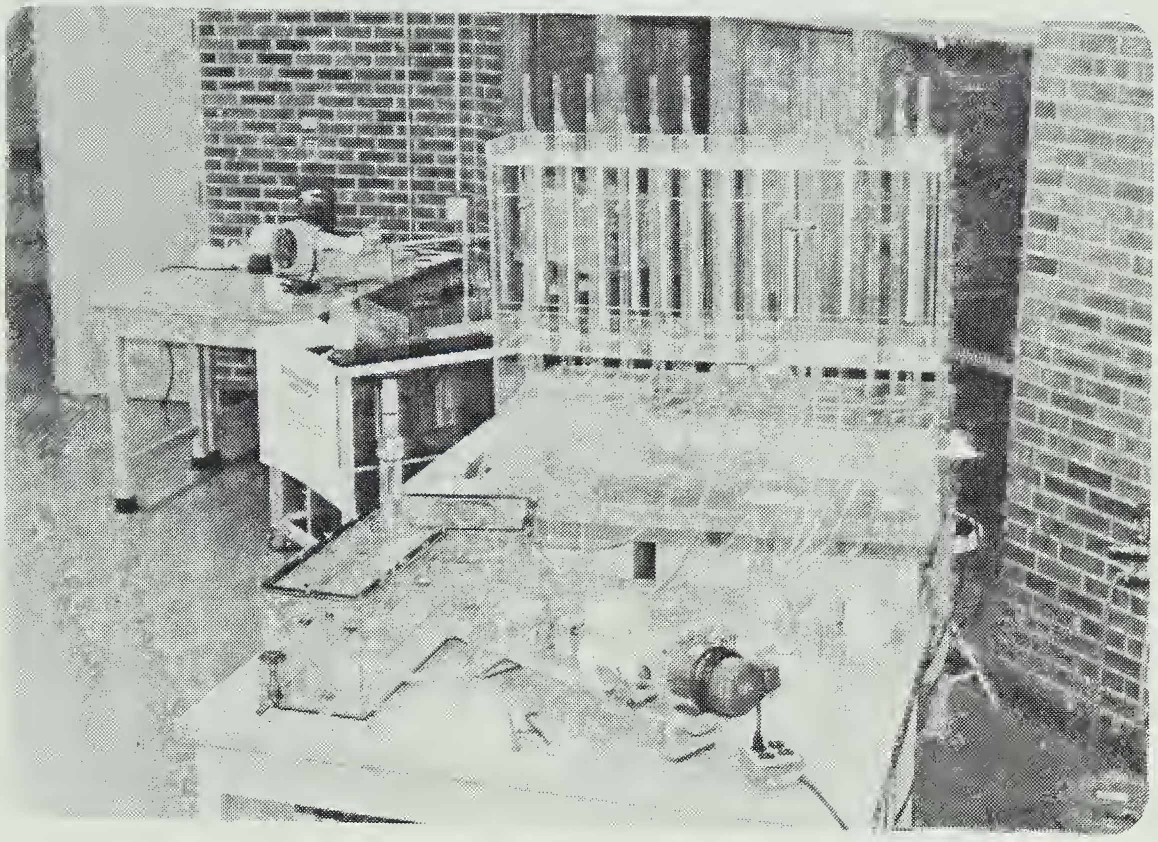


PLATE I

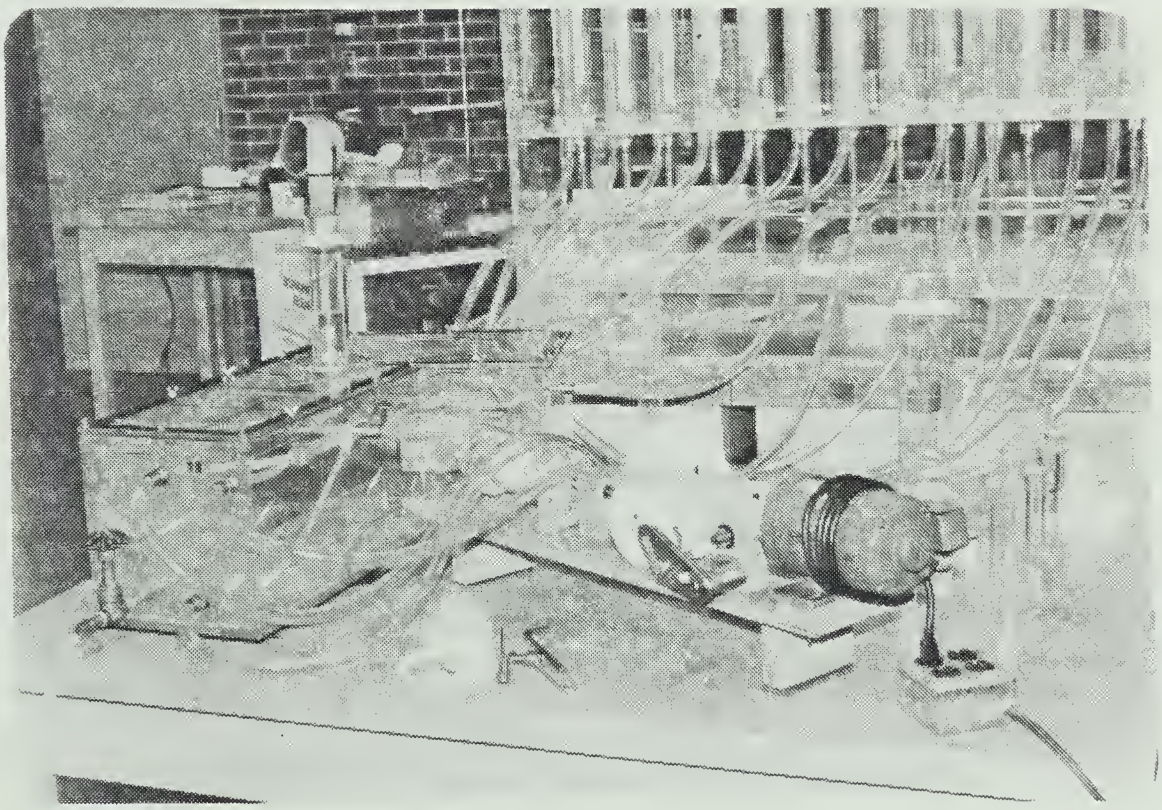


PLATE II

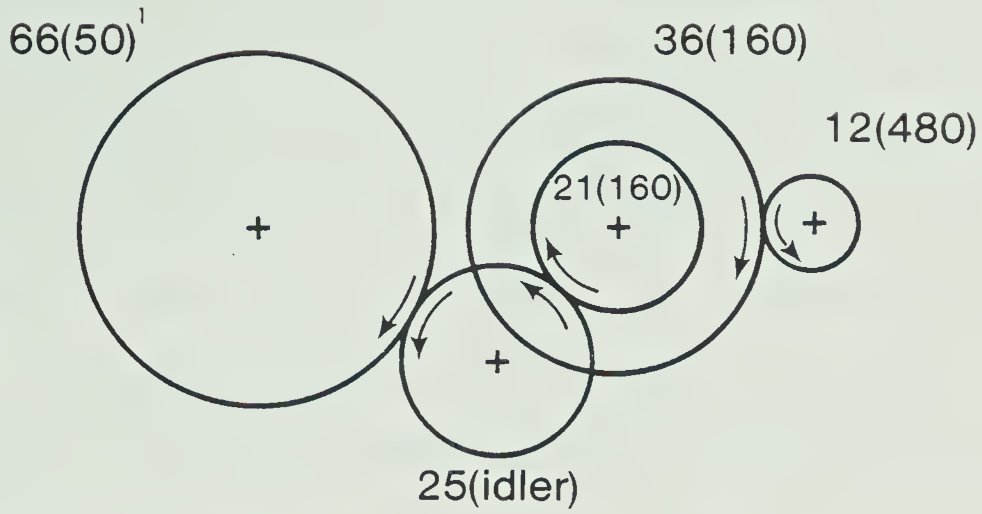


Fig. 2.2a. Gear Train for 50 beats/min

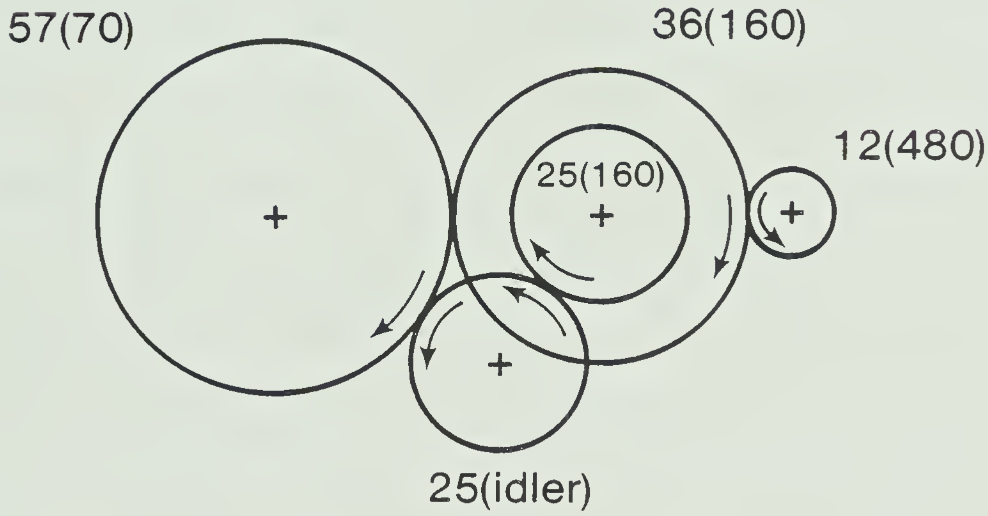
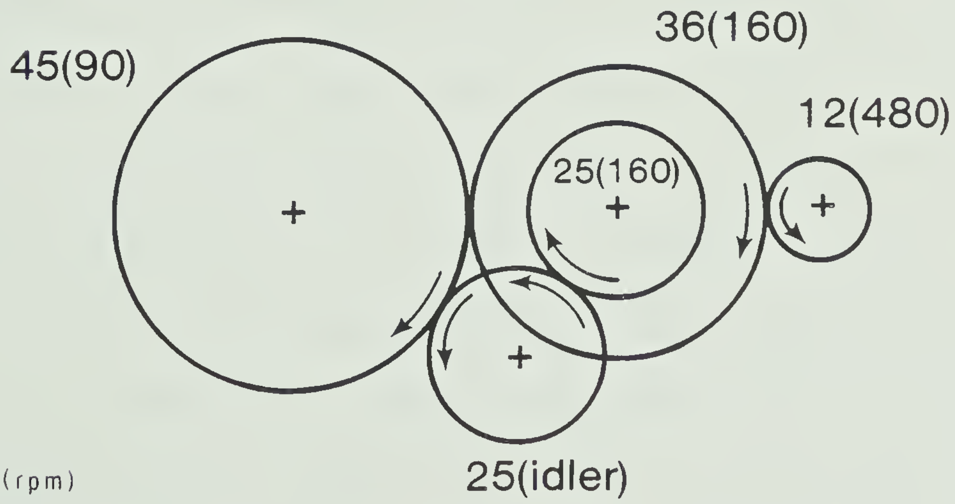


Fig. 2.2b. Gear Train for 70 beats/min



[1] Number of teeth (rpm)

Fig. 2.2c. Gear Train for 90 beats/min

Not to scale

the experiments covered in this phase gave an output speed of 50,70 and 90 rpm. The speed of 70 rpm corresponds to the normal heart rate of an average adult (Philip and Dorothy, 1971) whereas the other two speeds represent the abnormal pulse rate for the same individual. On the other side of the shaft, through the final driven gear, a groove cam was mounted and a roller follower guided in the groove was used to drive the piston.

The cam was cut in accordance with the velocity profile actually found at entrance to the aorta (Fig 2.3) (Anliker et al., 1977). This profile was slightly modified (Fig 2.3a) in the sense that the negative flow portion at the end of the ejection phase was not included because it is generally associated with the backflow that occurs as a result of the dilatation of the arteries and closure of the aortic valve. As the valve closes, at the end of the systole, the fluid keeps flowing because of its inertia and leaves behind a low pressure region in the aorta very close to the valve. At the same time the aorta has dilated during the systole and holds more blood than its capacity at normal size. The blood which is close to the wall rushes towards the valve to fill the low pressure region created by a sudden valve closure and the inertia of the fluid moving with a higher velocity near the axis. Since such a backflow is inherent in the system, this action was not included in the cam profile. Caro (1978) associates this backflow to the switch-over of the pressures in the left ventricle and

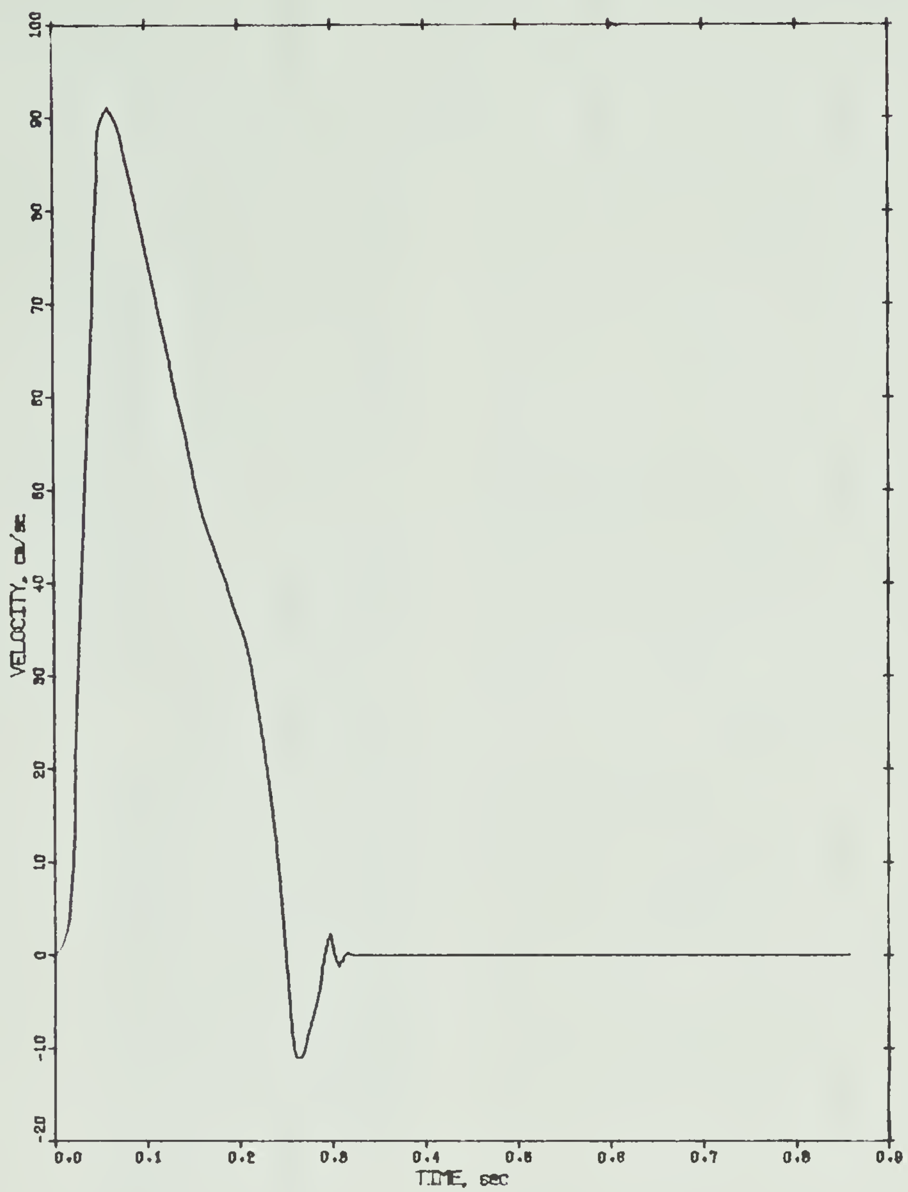


FIG 2.3 .. ACTUAL VELOCITY PROFILE

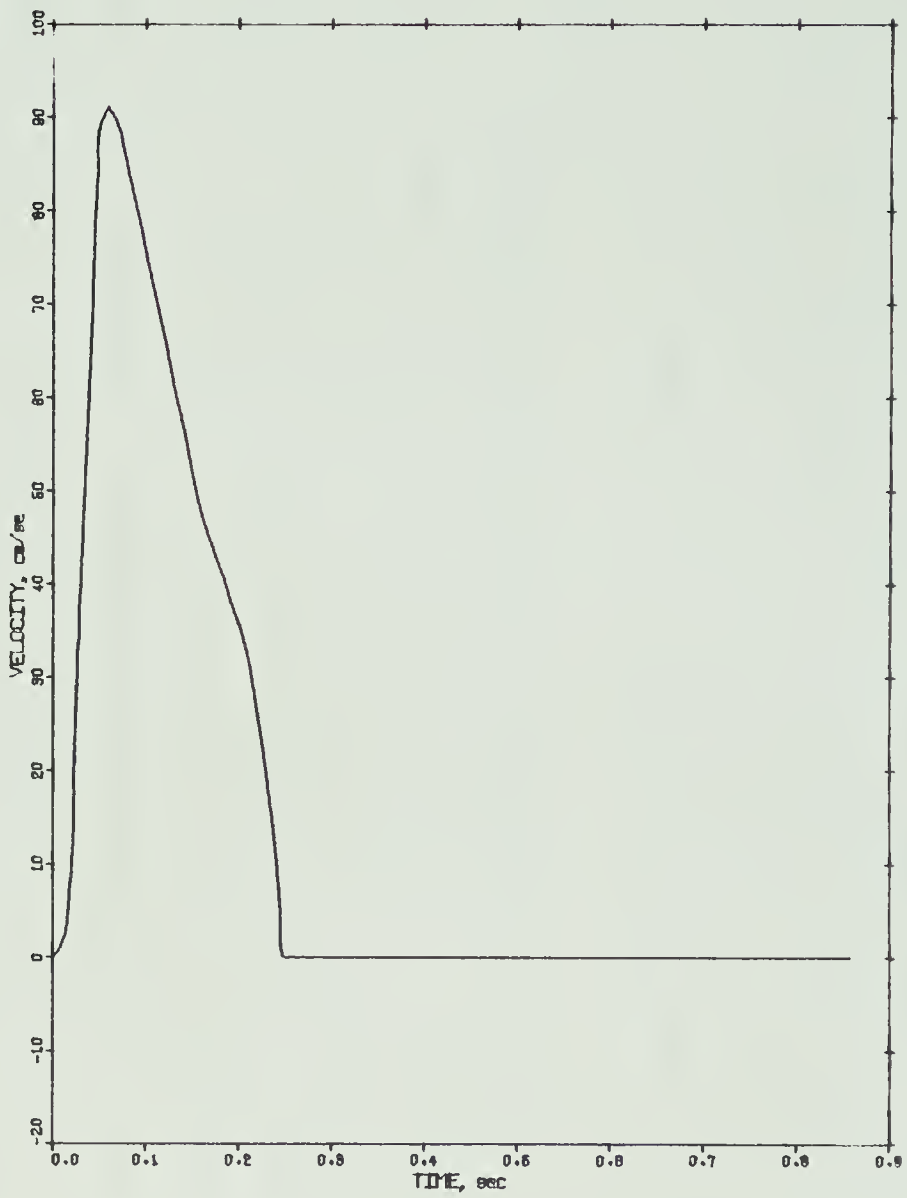


FIG 2.3a .. MODIFIED VELOCITY PROFILE

the aorta. The pressure in the ventricle rises to open the aortic valve and then drops, as the heart muscle relaxes, to a level when the pressure in the aorta is more than that in the left ventricle. This forces the aortic valve to close and, before it closes, some blood is pushed back into the ventricle.

The second modification in the profile is also associated with the dilatation of the aorta. After the end of the systole, the aorta relaxes to its normal size and, in doing so, ejects the additional volume held by it during the systole. This feature of the aorta helps in smoothing out the flow in addition to generation of a pressure pulse. The second rise in the velocity/flow profile is mainly associated with this property and the cam profile did not include it in the design because the dilatation of the aorta was simulated by the model itself. Since the model used in the experiments was an elastic model which dilated during the systole, as the normal human aorta does, this action corresponds to the second peak of the velocity profile. This also helps in a smooth dampening of the flow in the arteries.

For these reasons, though the cam was designed according to the slightly modified velocity profile of Fig 2.3a, the actual profile at entrance to the aorta has the features of the natural profile. The details of the cam design are given in Appendix B.

A 4.8 cm diameter piston was driven by the connecting rod, the other end of which had the roller follower guided by the cam. A needle bearing was used as the follower. The exit from the cylinder led to the model of the left ventricle which was divided into two parts with a surgical rubber diaphragm. This model of the left ventricle was designed for a maximum capacity of about 200 ml. It had two ports, inlet and outlet, located adjacent to each other. These ports were controlled by one-way, prosthetic, ball-type heart valves. The diaphragm kept the working fluid separate from the fluid displaced by the piston. The action of the piston activated the diaphragm in such a way that with every backward movement of the diaphragm, the fluid representing blood was sucked from the main reservoir into the left ventricle through the inlet valve; the outlet valve, opening into the aorta, remained closed during this period. During the forward movement i.e., when simulating the contraction of the heart, this volume was ejected into the aorta in accordance with the profile dictated by the cam; the inlet valve remained closed during this phase of the cycle. The total ejection period was approximately 30 percent of the total duration of each pulse. This corresponds to about 0.25 seconds at a pulse rate of 70 and, on the cam, to 105° of the cam rotation. During the remainder of the cycle, the left ventricle was filled with the fluid from the reservoir.

Between the piston and the model of the left ventricle, provision was made to control the pumping efficiency of the heart. In the space provided, an inverted cylinder with an air chamber on the top could be mounted so that, during the systolic action of the heart, some of the fluid could go into the chamber thereby compressing the trapped air whereas the rest would deform the diaphragm accordingly. This means that though the heart rate stays the same, the cardiac output could be controlled. The amount of the air trapped in the air chamber can control the pumping efficiency from 0 to 100 percent.

2.2 Reservoir containing the Model

The outlet port of the left ventricle opened in the reservoir which housed the model of the aorta. The aortic arch was mounted on this port so that the left ventricle discharged into the aorta. Since the arterial system under investigation was made in sections, these sections were joined with brass connectors and the complete model was suspended in the reservoir. Anticipating high velocities and the corresponding reaction of the model, the movement of the arteries was restricted by supporting them at various locations and this was done without affecting their dilataion properties i.e., the arteries were free to dilate even when their overall motion was restricted. Thin brass wire was used for the three-point suspension at each location; brass rods and hooks were mounted in the reservoir

for holding the wire. The suspended model represented the arterial system oriented for the resting position.

The reservoir was filled with water in order to pressurize the model which was immersed in it at all times. The water level in the cylinder above the reservoir was maintained to balance the hydrostatic pressure acting inside the arteries because of the head in the main reservoir containing the working fluid. This resulted in a normal starting of the pulses i.e., without any initial dilatation (other than that caused by the normal physiological pressures) or contraction of the arterial system.

The reservoir housing the model had 14 brass connectors located at its walls and the different branches were connected to the appropriate connector so that the flow through these arteries could be led to the measurement system.

2.3 Measuring Arrangement

The flow was measured by collecting the volume over a certain interval of time. Tygon tubing was used to lead the flow from the arteries to the measurement system. Particular attention was given to the position of the tubing and a thick-walled tubing was used to avoid any flexure which could have represented a blockage itself. The length of the tubing was kept to a minimum together with a very smooth inner surface so that the losses were not significant to introduce any measurement errors. A correcting factor

was, therefore, not employed and the volume collected was assumed to be the actual flow through the arteries.

The flow from each artery was led to small plexiglass tubes of a constant diameter of 12 mm equipped with control valves. After passing through these valves the flow was identically diverted to a set of calibrated collecting tanks. Each cylindrical tank collected the flow from a different artery and was individually calibrated. The discharge level to the cylinders was at a height of about 100 cm from the level in the reservoir containing the model so that the physiological diastolic pressure of 80 mm of Hg was maintained in the system as the minimum pressure. The flow from all arteries was discharged in the cylinders at the same time. Flow from the two iliacs was collected in the same cylinder and so was done with the two coronaries; the flow from the two renals and the representative artery[2] was collected in a common cylinder, as well. In this way, a series of 11 collecting cylinders was employed for flow from 15 different arteries.

Each of the cylinders had a toggle valve attached to its bottom and this valve led the flow from the cylinders to the main reservoir, located beneath the series of cylinders, after the flow was recorded. The working fluid thus followed a closed cycle.

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[2]This artery represented all the other small branches of the arterial system which were not modelled, as explained in Chapter 3.

2.4 Viscosity of the Working Fluid

A value of 4.6 centipoise was selected as representative of the absolute viscosity of the blood (Rosenblatt, 1965). Most researchers and the reference books, however, give a lower value for blood viscosity--for example, Whitby and Britton (1950) give a range of 4.8 to 5.2 for the relative viscosity of the blood without any mention of the physiological state of the person or persons from which the samples were taken; Wintrobe (1967) gives an average value of 4.5 and Albritton (1952) quotes a figure of 4.7 as the relative viscosity of the human blood at 37°C. An overall average of, say, 4.7 corresponds to an absolute viscosity of about 3.25 cp for blood as the viscosity of water at the body temperature (37°C) is 0.692 cp (Albritton, 1952).

A common feature of the experiments conducted or referred to by these scientists, in support of their quoted figures, is that the capillary viscometers were employed to determine the viscosity. These viscometers work on the principle based on Poiseuille's law that the passage of fluids in capillaries of equal caliber, under the same pressure and at the same temperature, depends upon their inner friction /viscosity. A capillary viscometer is well suited for studying Newtonian fluids such as plasma, but is unsuitable for non-Newtonian fluids, including blood, for the viscosity of blood will depend upon the size of the sample that is studied; particular problems arise if the

dimensions of the sample sheared in the capillary viscometer are comparable with those of a red cell, or, if rouleaux forms, with their size (Caro et al., 1978).

The effect of the anticoagulant used has also not been discussed in most of the references. The tests referred to by Wintrobe (1967) requires only one drop of blood and may be carried out in 30 seconds. Because of the particulate nature of the blood, its apparent viscosity also greatly depends upon the tube diameter and this effect is more pronounced in small capillaries that form the test section of the capillary viscometers.

Rosenblatt (1965), on the other hand, employed a cone-and-plate viscometer in his experiments. This instrument has advantages over the capillary viscometers for the study of blood, chiefly because the sample is mostly sheared at something approaching a constant rate if the design of the instrument is correct and the shear stress is sufficiently high. This instrument also permits the study of a sample over an extended period of time. This kind of viscometer is recommended for precise viscometry of blood (Caro et al., 1978; McDonald, 1974).

The figure of 4.59 cp with a standard deviation of ±0.485 as representative of the viscosity of blood is based on an average of 117 normal males whose medical histories were carefully screened to eliminate any disease conditions which are known to influence viscosity (Rosenblatt, 1965). A volume of 2.0 ml was used for each test and it is claimed

that the anticoagulant used did not vary the viscosity beyond the standard error.

A constant shear rate of 230 sec^{-1} was employed during the tests. Since blood is a non-Newtonian fluid and its viscosity varies with the shear rate, this single rate of shear measurement of the absolute viscosity does not adequately describe the behaviour of the fluid; but it may be used to predict the behaviour of blood in larger vessels. With this shear rate the adhesiveness and aggregation of red blood cells was reduced to a minimum (Rosenblatt, 1965). Moreover, above shear rates of 50-100 sec^{-1}, the apparent viscosity is practically constant (Whitmore, 1968).

Since the present study was confined to large vessels only and the fluid behaviour in capillaries was not required, the figure of 4.6 cp was selected for the absolute viscosity of the working fluid. The required viscosity was obtained by an acqueous-glycerol mixture having 36% of the available glycerol, by volume. Zephiran chloride, a surgical antiseptic and germicide, was added to the working fluid to prevent any bacterial growth. This chemical was added in a proportion of 1:750 parts of the working fluid and was not found to effect the viscosity with this small concentration. The mixture had a density of 1.1 g/cm^3.

Weiting, (1968) claims that 36.7% glycerol, by volume, when mixed with (distilled) water represents blood. This mixture was found to have a viscosity of about 4.7 cp and this figure also falls in the range quoted by Rosenblatt

(1965). Anliker (1977) used a value of 4.9 cp for the viscosity of fluid used in his model and this value again lies well within the standard deviation referred above, for normal healthy adults.

CHAPTER 3

MODEL OF THE AORTA AND ITS BRANCHES

3.1 Geometry of the Model

In preparing the model of the aorta, all the main branches except the small arteries were included with emphasis on the arteries responsible for the blood supply to the brain. Some of the arteries emanating from the descending aorta were represented by a single artery because the study of the disease was not extended to lower regions of the arterial system. This artery also accounted for the flow through the intercostal arteries.

The fact that the geometry and size of the aorta and its different branches, like all other organs, vary considerably from individual to individual posed great difficulty in selecting the most suitable values for the model. However, the final geometry and measurements were selected by averaging the available information in a way that the majority of human beings (adults) are covered within a narrow range about these figures.

The geometry of the model with the size of various branches and other corresponding parameters is shown in Figure 3.1 and the accompanying Table 3-1.

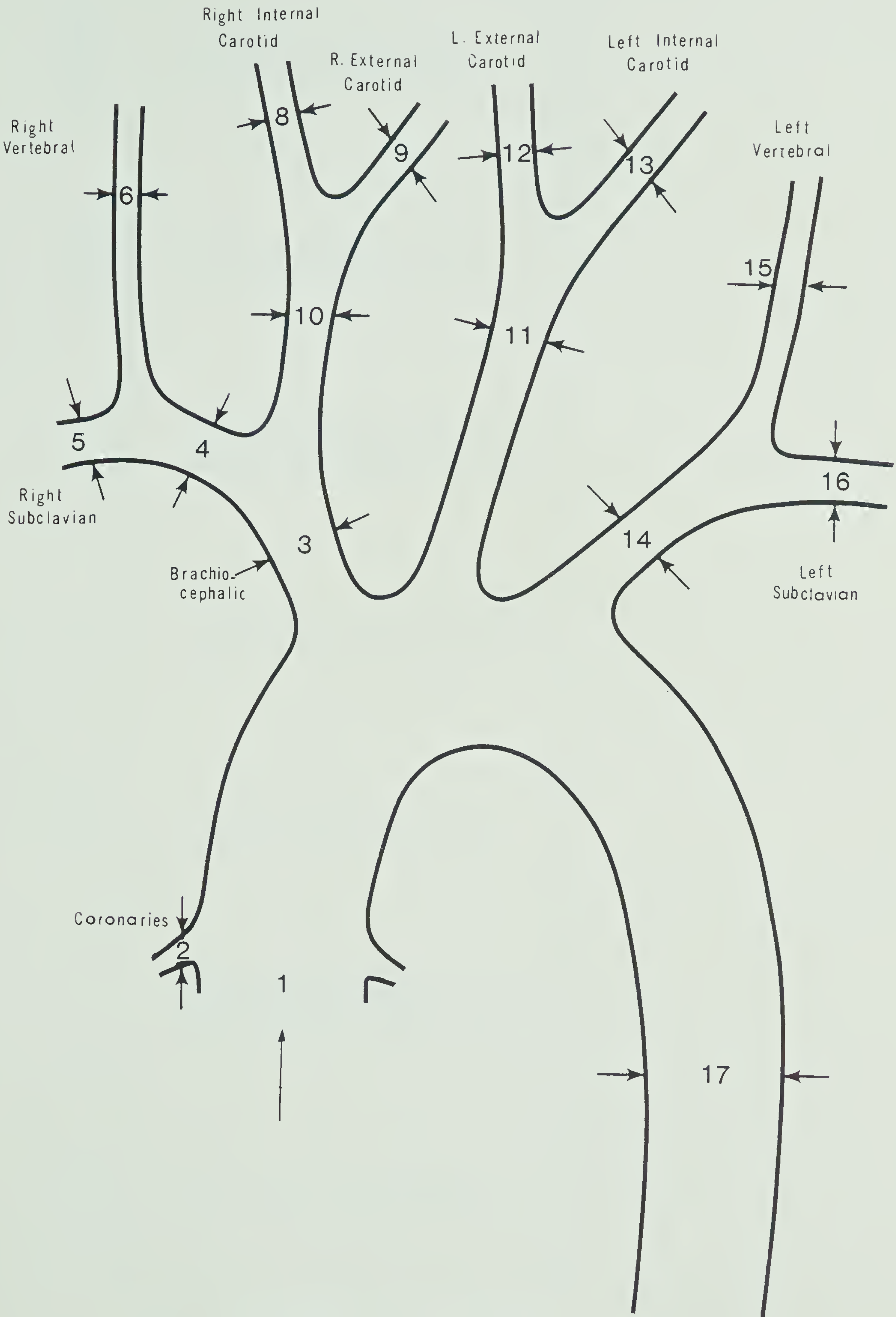

FIG 3.1 .. GEOMETRY OF THE AORTA

Not to scale

TABLE 3-1 PARAMETERS AT VARIOUS LOCATIONS (Normal Pulse Rate)

LOCATION	DESCRIPTION	DIAMETER mm	FLOW %	FLOW cm^3/min	AVERAGE REYNOLDS NO Re	UNSTEADINESS PARAMETER
1	ENTRANCE	29.0	100.0	5680.0	994	19.20
2	CORO	-	4.0	227.2	-	-
3	BRAC	13.0	12.0	681.6	266	8.61
4	RSCB	8.0	5.0	284.0	180	5.30
5	RSCL	7.0	3.0	170.4	124	4.63
6	RVER	4.0	2.0	113.6	144	2.65
8	RINC	5.6	5.0	284.0	257	3.71
9	REXC	5.6	2.0	113.6	103	3.71
10	RCCA	8.0	7.0	397.6	252	5.30
11	LCCA	8.0	7.0	397.6	252	5.30
12	LEXC	5.6	2.0	113.6	103	3.71
13	LINC	5.6	5.0	284.0	257	3.71
14	LSCB	8.0	5.0	284.0	180	5.30
15	LVER	4.0	2.0	113.6	144	2.65
16	LSCL	7.0	3.0	170.4	124	4.63
17	-	20.0	-	-	-	-
-	RENS	-	25.0	1420.0	-	-
-	ILIA	-	16.0	908.8	-	-

The size of aorta at entrance was taken as 29 mm (internal diameter) and this average figure is almost undisputed in most of the literature (Rodkiewicz, 1979; Furukawa et al., 1976; Meschan, 1975; Reul et al., 1974; Davis, 1967; Synder et al., 1968; Anson, 1966; Nathaniel, 1949). Some researchers, of 1940's and earlier, give a lower figure which can be associated with the fact that no feasible technology for *in vivo* measurements or preserving the arch of a dead person was available at that time. The arteries collapse very soon after the biological function of the body ceases.

Three main branches emanate from the aortic arch, namely, brachiocephalic, left common carotid and left subclavian, the first one being the largest of the three. These arteries are responsible for blood supply to the upper portion of the human body, for example, the brain, arms, neck, facial region, etc.

This pattern in which the three branches arise from the arch separately accounted for 74% of the cases in American whites in a study carried out on 216 subjects (McDonald and Anson, 1940). A similar study of 111 American whites showed 77.4% to be of this variety (DeGaris et al., 1933). Since the anatomy has not changed much with time, this pattern is still found as the most common configuration and is also referred to as the "textbook" pattern .

The two coronary arteries are the first branches from the aorta. These arteries are responsible for blood supply

to the heart itself and have an average internal diameter of 4 mm each (Lusted and Keats, 1978; Reul et al., 1974).

The brachiocephalic artery has a mean diameter of 13 mm (Anson, 1966) and it branches into the right common carotid and the right subclavian which have a mean internal diameter of 8 mm each (Balasubramaniam, 1980; Rodkiewicz, 1979; Synder et al., 1968). The left common carotid and the left subclavian were also chosen to have the same dimensions as their counterparts on the right side.

The left and right vertebrals, which carry a part of the total blood requirements of the brain, emanate from the left and right subclavian, respectively. On basis of angiographs available with the Department of Anatomy, University of Alberta, the lumen diameter of the vertebral arteries was taken as 4 mm each. The left and right subclavian, after giving of the vertebrals, have an internal diameter of 7 mm each (Reul et al., 1974).

The common carotids, after passing through the neck, bifurcates into internal and external carotids. The left and right internal carotids are the main arteries supplying blood to the brain whereas the two external carotids take care of the facial region, skull, etc. Though the volume of blood flowing through the internal carotid is more than twice as compared to the volume flowing through the external carotid, it has been observed that, in adults, the two branches are approximately same in size (Anson, 1966). Again, basing figures on the information provided by the

Department of Anatomy and the available literature, the lumen diameter of the internal and external carotids was selected as 5.6 mm each.

The next main arteries originate from the abdominal aorta. The gastric, hepatic, splenic and intercostal arteries were simulated by a single artery because these arteries were not important from the point of view of the work undertaken. The internal diameter of this representative artery was chosen as 10 mm on basis of the expected flow. This artery also accounted for the superior and inferior mesentric and other small arteries given off by the aorta upto the iliac bifurcation.

The two renal arteries have an average internal diameter of 6 mm each (Reul et al., 1974; Anson, 1966).

At the end of the abdominal region, the aorta bifurcates into the left and right common iliacs each of which further branches into the external and internal iliacs. The internal diameter of each of the common iliacs was taken to be 9 mm (Reul et al., 1974; Anson, 1966) and, once again, these arteries were modelled for flow collection purposes only.

The main aorta decreases in diameter as it gives of branches. In the model, this feature was simulated by tapering it from 29 mm at entrance to 20 mm at just above the location of the celiac trunk (Meschan, 1975; Nathaniel, 1949) and to 17.3 mm at the iliac bifurcation (Lusted and Keats, 1978; Synder et al., 1968; Davis, 1967; Nathaniel,

1949). After giving off its three main branches, the brachiocephalic, the left common carotid and the left subclavian, it has an internal diameter of approximately 23 mm (Meschan, 1975; Anson, 1966; Nathaniel, 1949).

3.2 Fabrication

The model of the arterial system was made in parts with sections made at locations where blockages had to be placed. The locations selected are the most susceptible zones for inception of atherosclerosis, as explained in Chapter 1. The aortic arch and the arteries emanating from it constitute ten sections with provisions of blockages at nine different locations (Fig 3.2). The lower part was made in two sections: the descending aorta upto the lower abdominal region and the iliac bifurcation, thereby leaving provision for extending the study of the effects of atherosclerosis in the lower portion of the arterial system.

The model arteries used were elastic finished product having capability of temporary dilatation during the systolic action of the pulsatile unit.

The first stage of fabrication consisted of machining solid pieces out of plexiglass and/or aluminium and then finishing them to a smooth surface and proper shape. A mixture of sealant silicone and toluene was then prepared to make the elastic model. Toluene acts as a solvent for silicone and the mixture gels as it evaporates. The solution is ready for use when it flows freely and does not

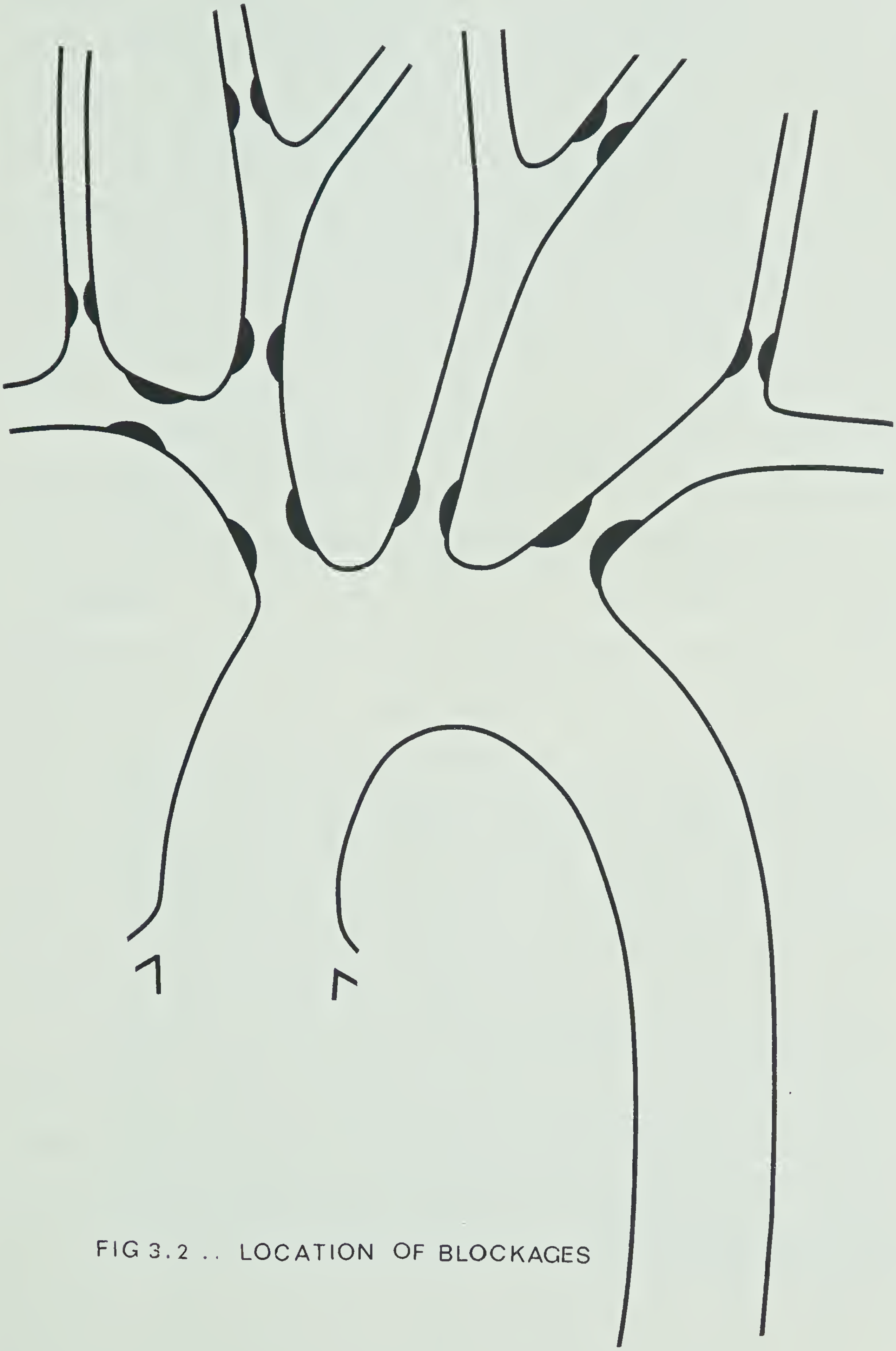

FIG 3.2 .. LOCATION OF BLOCKAGES

Not to scale

gel if exposed to room conditions for a few minutes; more toluene is added, otherwise. The homogenity of the mixture also played an important role in the quality of the finished product. Since toluene attacks plexiglass, the rigid model had to be coated with an inert substance. Vaseline paste was used in this case as the shielding layer. Besides preventing a reaction of toluene with plexiglass, vaseline also acted as a lubricant to ease the removal of the elastic model from the solid sections.

The solid model was given a dip in the tin-foil pan containing the silicone-toluene mixture and then held in a rotating chuck so that the mixture could spread out evenly throughout the surface (Plate 3). Rotation also helped preventing any break-up of layers which occured if the model was dried otherwise. The speed of chuck was also a controlling factor in the final finish of the product. A too fast or a too low speed resulted in agglomeration of silicone thereby producing somewhat harder and less elastic spots within the wall. An approximate speed of 75 rpm was found to give excellent results.

Evaporation of toluene was responsible for drying of the layer. Each layer was allowed to dry out sufficiently, under room conditions, before another layer was applied. Quick-drying sometimes resulted in appearance of small cuts on the surface and within the wall; over-drying produced wrinkles when the next layer was applied, and, under-drying produced an uneven surface at the same stage.

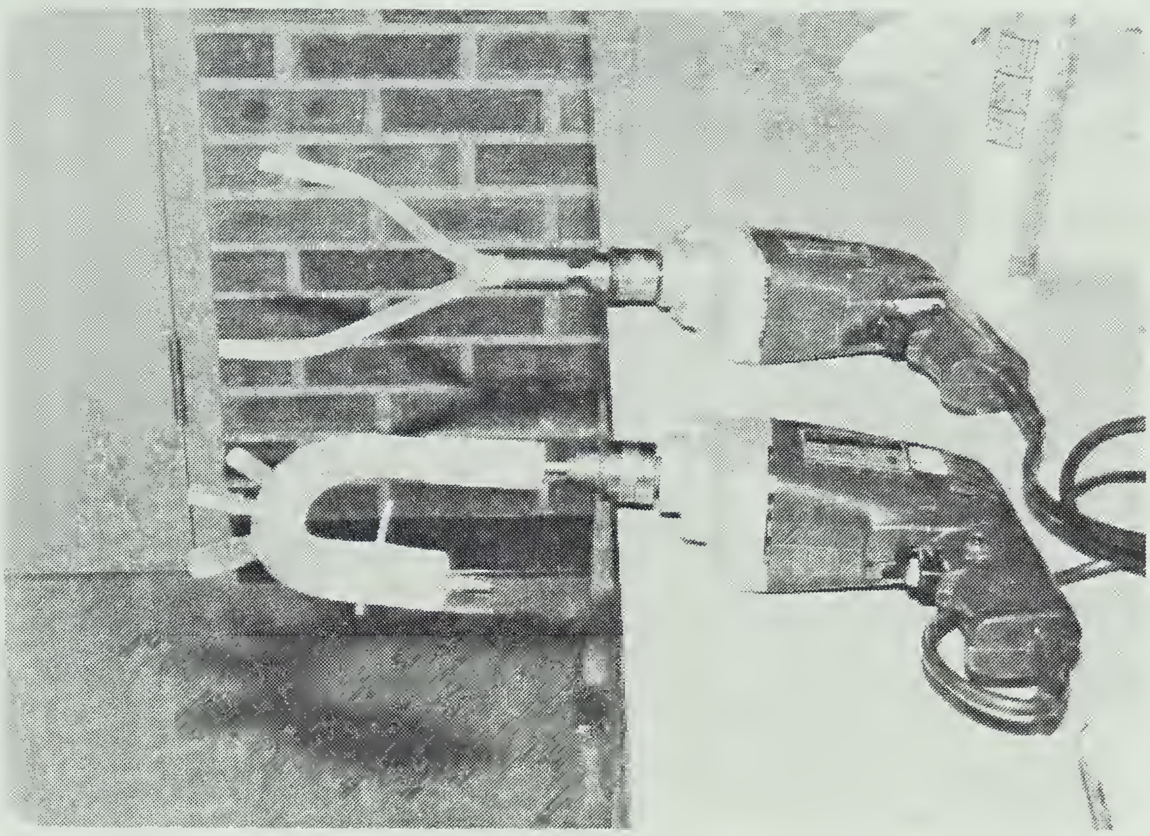

PLATE III

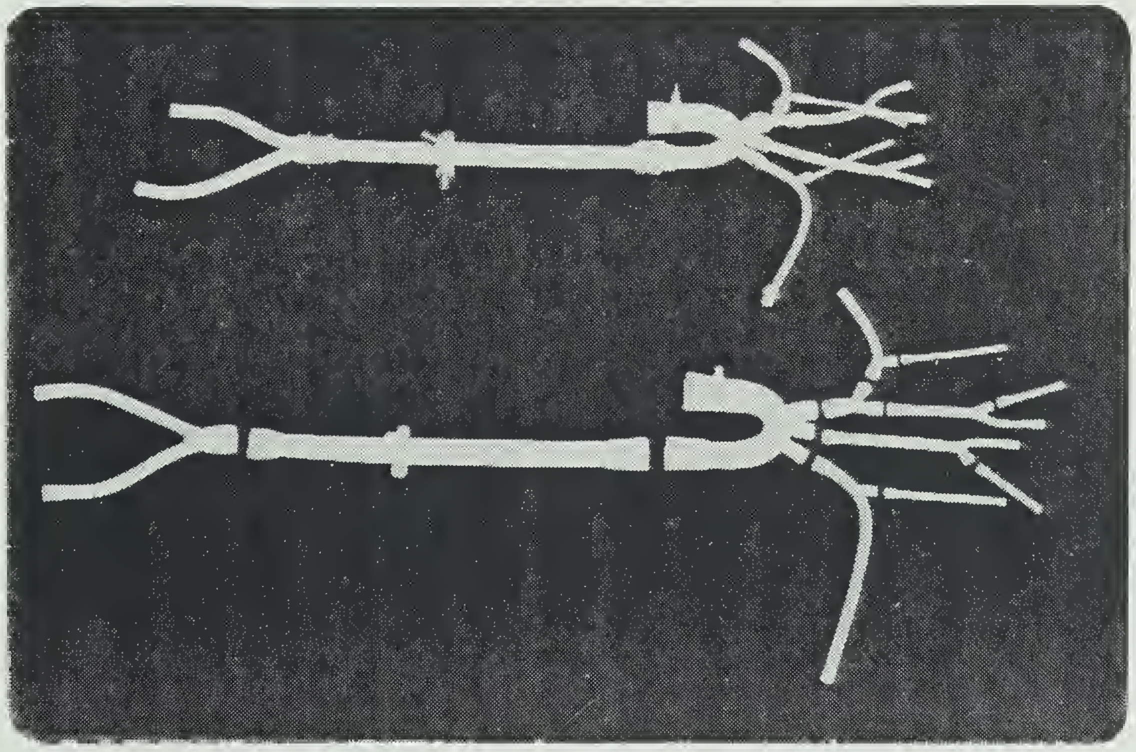

PLATE IV

An approximate interval between two consecutive layers was 10-15 minutes for a fine finish with slightly less time allowed between the first two layers; it took a little longer for the larger parts. Moreover, upto ten layers for smaller arteries and from 15-20 layers for the larger ones were required for the adequate wall thickness. Toluene had to be added to the mixture from time to time to keep it in the flowing state but at the same time it was observed that a very thin mixture, besides requiring more layers, produced a fairly rough finish. On the other hand, a very thick mixture resulted in a lumpy appearance because it dried out before spreading uniformly over the surface. In both these cases, the elasticity was affected but the smoothness of the inner surface was still dependent upon the finish of the solid sections.

After obtaining the desired thickness, the coated model was left on the rotating chuck for about three hours and then held undisturbed for a curing period of 24 hours. Any irregularities developing on the surface during the first few hours of the drying period were repaired immediately with a fresh silicone-toluene paste. The elastic model was then removed from the plexiglass or the aluminium mould. The ends were cut to size and then reinforced with very thin, freshly prepared, silicone-toluene solution. This prevented any initiation of rupture at the ends. The elastic model attained its maximum strength in seven days.

The solid models for the intricate shaped arteries were made in two or more pieces so that these could be detached and the elastic model removed without getting damaged. The detached pieces were reusable for duplicating the model, when required.

3.3 Flow Distribution

The amount of blood flowing to the brain has an almost undisputed range of 50-55 ml per minute per 100 gm of brain, which is equivalent to about 750 ml per minute, for a normal person at rest (Schottelius, 1978; Middleman, 1972; Philip and Dorothy, 1971; Guyton, 1966). For a cardiac output of 5.5 L/min, this quantity measures about 14% of the total flow. The main arteries supplying this volume to the brain are the two internal carotids and the two vertebrals, the major portion being carried by the carotids. About 7% of the total cardiac output flows through the common carotids (Reul et al., 1974) and, after bifurcation of the common carotid, the average flow division between the internal carotid and the external carotid is 70:30 (Balasubramaniam, 1980). This ratio gives the flow volume as 2% and 5% of the total cardiac output through each of the external and internal carotids, respectively. In this way, about 70% of the total blood requirements of the brain, or about 10% of the total cardiac output, passes through the internal carotids. The remaining portion of the requirement of the brain, equivalent to about 4% of the total cardiac output,

flows through the two vertebrals.

The blood volume through the subclavians was taken to be 5% of the total cardiac output (Reul et al., 1974). Since the vertebral arteries emanate from the subclavians, the volume carried by each of the subclavian, after branching off the vertebrals, is 3% of the total cardiac output.

The brachiocephalic artery divides into the right subclavian and the right common carotid so it should carry the volume to meet the requirements of both these arteries. The blood flow through the brachiocephalic is, therefore, 12% of the total cardiac output.

The figures as given above indicate that 24% of the total cardiac output is taken up by the three arteries branching from the aortic arch: brachiocephalic, left common carotid and the left subclavian. The two coronary arteries which branch out just at entrance to the aorta take 4% of the total cardiac output to feed the heart itself (Reul et al., 1974). This implies that the remaining 72% of the output flows downwards through the descending aorta.

About 25% of the total cardiac output flows to the kidneys and the major portion passes through the two renals (Reul et al.,1974; Guyton,1966). The flow through the superior and inferior mesentric arteries accounts for 22% of the flow (Reul et al.,1974) and about 9% passes through the small arteries emanating throughout the descending aorta (Reul et al.,1974). In this way, the representative artery

in the model passed 31% of the total output.

The remaining 16% of the total cardiac output is divided at the iliac bifurcation, 8% flowing through each of the common iliacs (Reul et al., 1974).

These figures for the flow distribution were also confirmed by the Faculty of Medicine, University of Alberta, and this distribution was obtained in the system before putting any blockages.

The pattern of the arterial system was selected to represent a majority of the normal adults as discussed earlier. This also includes the angles and the locations at which the branches emanate and the course followed by them within the body.

3.4 Blockages

It is interesting to note that though there are different theories regarding the causes and development of atherosclerosis, the specific location of the lesions is almost undisputed.

The research done in this area confirms that atherosclerosis does not occur at random locations. *In vivo* studies carried out by Rodkiewicz (1975) on rabbits shows the sites of atherosclerotic formations as the zones of diminished lateral pressure or the separation regions. Such zones are generally the areas following a bifurcation or a branching site. His experiments also show the stagnation zones as the favourable locations for the development of

atherosclerosis but these sites are still controversial among other researchers. Experiments carried out on dogs in which atherosclerosis was produced experimentally by altering hydraulic characteristics under controlled conditions also confirms that the progressively occlusive pathological changes occur consistently at sites of predilection characterized by a diminished lateral pressure (Imparato et al., 1961; Texon et al., 1960). The localized decrease in the static pressure at these specific zones produces, in effect, a local suction action or tensile stress upon the intima at some phase of pulsatile flow in the cardiac cycle. The intima is subjected to the lifting or pulling effect of the flowing blood upon the endothelium and subjacent cells. The response is a local biological change--a reparative or reactive thickening which results from the proliferation of the endothelial cells (Haust, 1976). Many other researchers also confirm the standard sites.

On the basis of these cosiderations the blockages which represented occlusion due to atherosclerosis were placed at the specific sites predicted by applying the principles of fluid dynamics.

Blockages representing 50%, 75% and 100% occlusion of an artery were designed for each section. All the blockages, regardless of their size, had a common geometry as shown in Figure 3.3. Since the flow distribution was more important than the flow pattern in the present study,

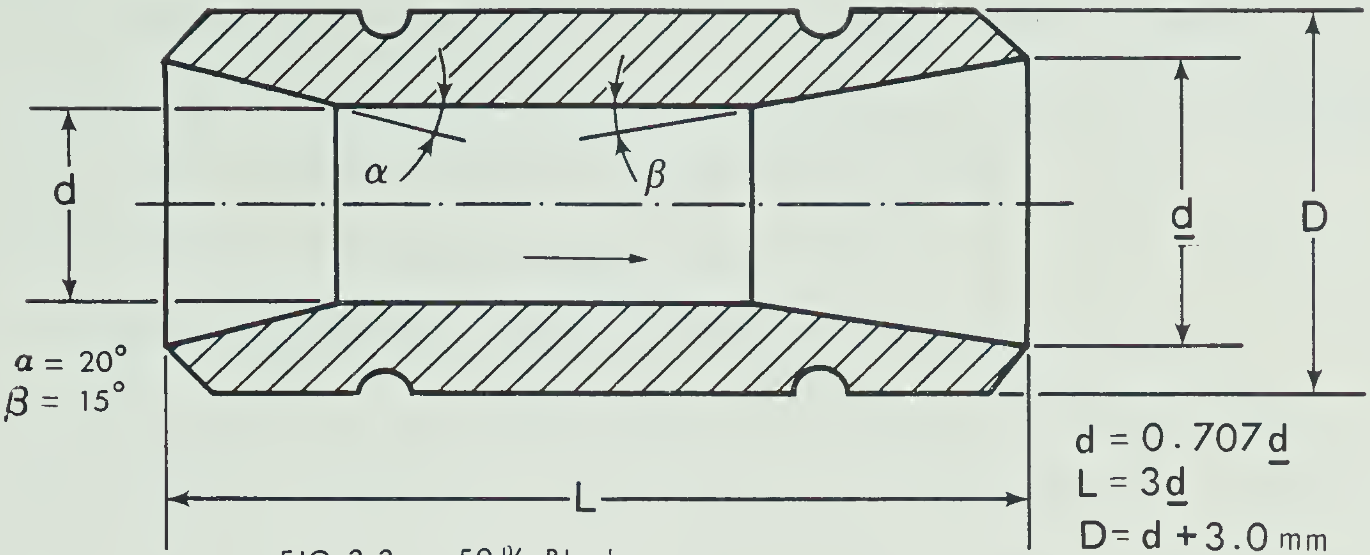

FIG 3.3a .. 50 % Blockage

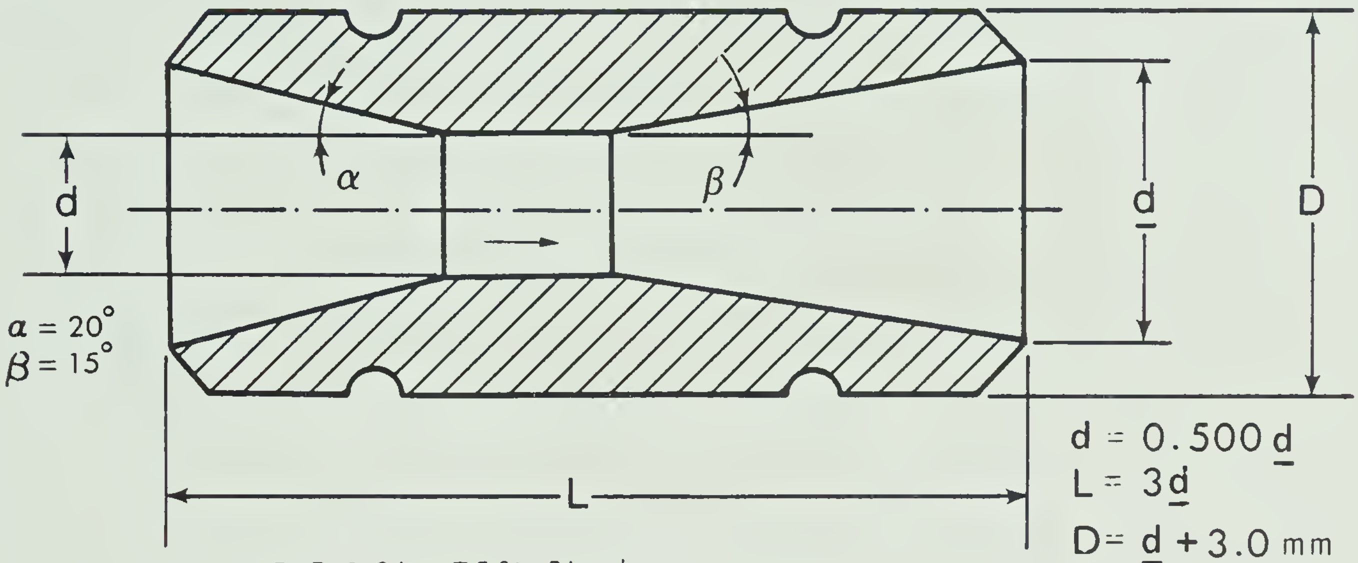

FIG 3.3b .. 75 % Blockage

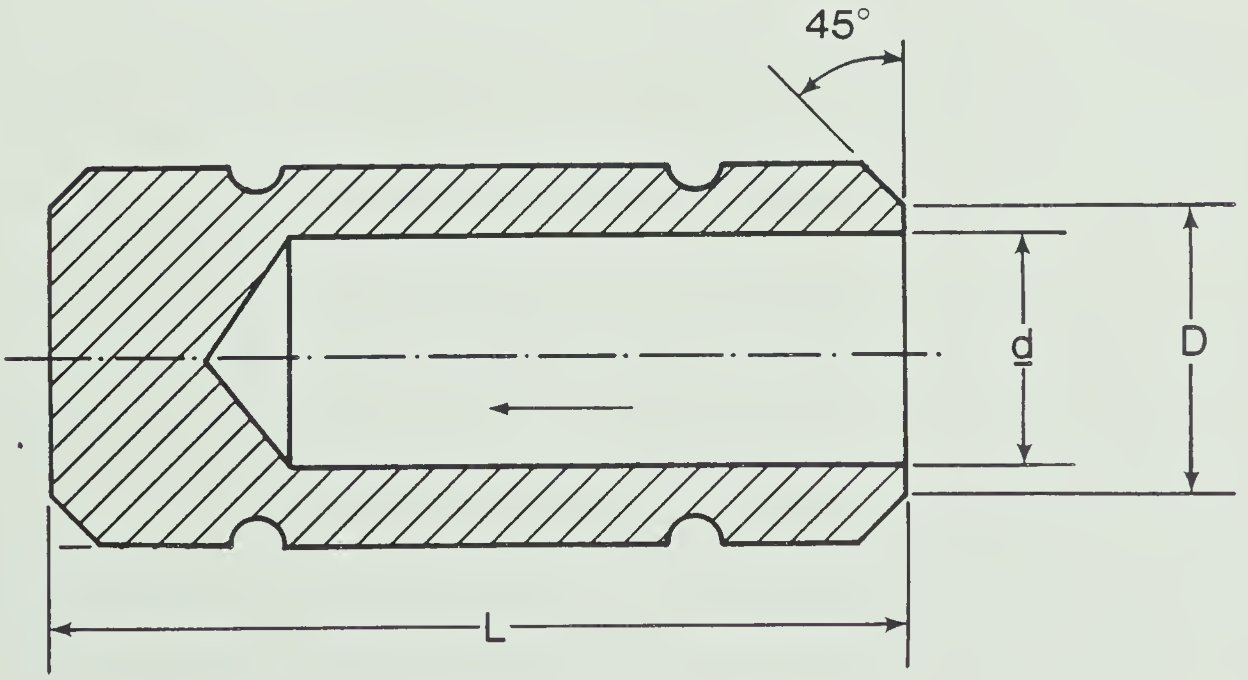

FIG 3.3c. 100 % Blockage

Not to scale

FIG 3.3 .. BLOCKAGES

the inlet and the outlet of the blockages was designed to avoid the orifice action at the passage through the blockage which could have reduced the effective area of flow considerably, causing significant errors in the results. All sharp edges were also rounded off to prevent any disturbance in flow even where the rate of flow was small. The internal shape was identical to a convergent-divergent diffuser and the angles were selected to avoid any secondary flows.

CHAPTER 4

EXPERIMENTAL PROCEDURE AND PARAMETERS

4.1 Procedure

The first and the most important phase of the experiments was to obtain a reference flow distribution for a normal individual, i.e. when various sections of the arterial tree were connected by simple connectors equal to the size of the corresponding branch; no blockages were introduced. This was accomplished by regulating the control valves and can be described as a kind of an iterative procedure.

The pulsatile unit was turned on and the fluid was pumped to a height of over 100 cm before it was discharged into the measuring cylinders. The unit was stopped and the level in each of the leading tubes was allowed to settle at the 100 cm level which was very close to the discharge level. This step served two purposes, the first one being that when the pulsatile unit was turned on at this stage, all the arteries started discharging fluid at the same time. This eliminated any errors that could have been introduced, otherwise, in determining the flow distribution. The second reason, which is more important, is that by pumping the fluid to a level of 100 cm before discharging ensures that

the arterial system is under some kind of initial pressure. This initial head of 100 cm of the working fluid corresponds to the physiological diastolic pressure of 80 mm of Hg thereby representing pressure conditions of a normal human being. In this way, it was assured that the minimum pressure in the system at any time during the flow was not less than the normal diastolic pressure representative of an alive person. The arteries, therefore, did not collapse during the diastole when no fluid was ejected into the aorta. Since the model was always surrounded by a fluid in an independent reservoir, the 100 cm was the differential head so that the 80 mm of Hg was the net pressure acting on the inside.

After starting the pulsatile unit with the fluid near the discharge level, the flow was collected for two minutes (a two minute period reduced the errors, if any, by half when the flow was averaged over a one minute reference period). The distribution was then compared with the normal expected flow figures and the valves were adjusted accordingly. The same procedure was repeated and the normal flow distribution was obtained after 45 measurements and adjustments. These figures (given as case 1 in Table A-4 of Appendix A) were within ±1% of those mentioned in Chapter 3 and were reproduced twice within a tolerance limit of ±1%. The valves were then sealed-off at the reference position. This normal distribution was obtained for a pulse rate of 70 which represents a majority of normal human beings. The

distribution at 50 and 90 beats per minute, which are abnormal heart rates, was slightly different from that at 70 beats per minute. The three distributions were, however, recorded for reference purpose and appear as Case 1 in Tables A-3 through A-5. All these results were also reproduced twice within ±1%.

The next phase of the experiments was to simulate atherosclerosis in one or more of the branches and to study the corresponding effect on the flow distribution with emphasis on the flow reaching the brain. Sixty-six different combinations, representing 66 different cases of the arterial stenosis (both mild and severe) were simulated and, for each combination, flow distribution was obtained at 50, 70 and 90 beats per minute. Each result was reproduced and an average of the two readings was recorded. A tolerance of ±1.5% was allowed for reproduction but most of the results were reproduced within ±1%.

In order to simulate a particular case of atherosclerosis, the fluid level in the reservoir containing the model was lowered and the top was removed. The connector from the particular artery involved was then replaced by the required brass blockage designed as explained in Chapter 3. The connector and the blockage for any particular branch had identical outer shape and dimensions so that a replacement did not affect the overall geometry of the arterial system under investigation because of a virtual lengthening or shortening of an artery. The

blockage was held in position by a thin wire which clamped the artery on to it. This was done for all the arteries that required to be partially or completely blocked-off for any particular case. A list of the combinations of blockages used to represent various cases is given in Table A-1.

The model was checked for any leakages or other imperfections (particularly at the point of insertion of the blockage/connector) by turning on the pulsatile unit. Since the model was fabricated in duplicate together with a few spare arteries, any damaged artery was immediately replaced. However, after any replacement, all the blockages were removed and the flow distribution was checked for any deviation from the reference values. No such case was discovered because of the identical duplicates.

After checking the model, the reservoir was closed and refilled to the same reference level. The fluid was pumped to the 100 cm level and the unit was started again. The flow was collected for two minutes and recorded. The results were reproduced within the tolerance limit. The gear train was then changed and, for the same set of blockages, the distribution was also recorded for the two other frequencies by repeating the procedure described above.

The reservoir containing the model was opened only when the combination of blockage had to be changed. All the procedure was repeated for every set of blockage as listed

in Table A-1. The 50%, 75% and 100% blockages were used, as and when required, depending upon the adversity of the disease in any particular artery. The experiments which showed a deviation from the reproducibility tolerance of ±1.5% were subject to repetition but, fortunately, this happened only in one case. After every few cases, all the blockages were completely replaced by connectors and the flow distribution was checked for any deviations from the reference figures of Table A-2 (Appendix A).

The distribution for all the cases was recorded and analysed with the aid of computer. The results obtained, both in digital and analog form, are given in Appendix A and discussed in Chapter 5.

4.2 Governing Parameters

The working fluid had the same kinematic viscosity as that of the normal human blood, the geometry and the size of the model represented the aorta of a majority of human beings, the velocity/flow profile at entrance to the aorta was the same as that produced by a normal heart and the heart rates were actually reproduced. Considering all these features of the system, the experimental conditions developed match the natural conditions from the fluid dynamics point of view and, therefore, the governing parameters which describe the flow are not of any significance as far as the geometric and dynamic similarity is concerned. However, for better understanding of the

situation and for later reference, the results are represented in terms of the two non-dimensional parameters namely, the Reynolds number, Re and the unsteadiness parameter, α given by

$$Re = \frac{DV}{\nu} \qquad 4.1$$

and

$$\alpha = \frac{D}{2}\sqrt{\frac{\omega}{\nu}} \qquad 4.2$$

respectively, where D is the lumen diameter of the artery, V is the velocity, ν is the kinematic viscosity of the working fluid and ω is the angular frequency. At the normal pulse rate the value for the average Reynolds number at entrance to the aorta is 1000 whereas for the unsteadiness parameter it is 19.2. These values lie well within the physiological range quoted by many scientists. The figures at other branches are given in Table 3-1.

As seen by the expressions 4.1 and 4.2, both the Reynolds number and the unsteadiness parameter give the ratio of the inertia forces to the viscous forces and their absolute value determines how much does one of these forces dominate the other. The parameter α, however, is also referred to as the unsteady Reynolds number for the flow as it indicates the relative importance of inertial and viscous forces in determining the motion within the time scale of

one period of oscillation (Caro et al., 1978). The information, in terms of the governing parameters, can be helpful when a mathematical analysis is done for the system; for example, at low values of the unsteadiness parameter (less than unity) the viscous forces dominate and the inertial forces can be neglected.

CHAPTER 5

RESULTS AND CONCLUSIONS

The results obtained are presented both in digital and analog form in Appendix A.

Figures A-1 through A-9 shows the effect of individual artery blockages (when only one branch is involved) on the blood flow to the brain. The adversity of the disease is simulated by reducing the lumen of the artery and the results are plotted for various Reynolds numbers used in the experiments. In almost all the cases it is observed that the cerebral blood flow is reduced more steeply when the atherosclerosis develops to block more than 75% of a particular artery. Also, in all the cases, the cerebral flow tends to reach an asymptotic value close to the normal reference values when the blockage is less than 50%. The trend is, however, monotonic and the flow reduces when the stenosis develops from 50% to 75% but the effect is not as pronounced as it is in the range from 75% to 100% blockage. The only deviation from this observation is shown in the case of the right subclavian with flow at a Reynolds number of 680 and the left vertebral at Reynolds number of 1300. In the latter case, the curve tends to approach a straight line if the flow at 75% blockage was identical to its

counterpart on the right side. Since every result was reproduced within very close limits, the possibility of an experimental error does not exist. The observed trend can, therefore, be attributed to the geometry of the arterial system. The deviation is not phenomenally concerning and the flow falls with increasing blockage. In the other case, however, the flow at a Reynolds number of 680 does not follow a monotonic behaviour with varying blockages. When the right subclavian is completely blocked-off, the cerebral flow is higher than the flow at partial blockage of the same artery. A complete blocking of the right subclavian indicates that the brain is not receiving any flow through the right vertebral so it is obvious from the experimental results that the balance is quickly and very efficiently taken up by the other three arteries responsible for supplying blood to the brain. This, however, does not happen at the other two Reynolds numbers.

A general comparison of the effect of same degree of blockage in arteries on the left side with their counterparts on the right side shows that the results are not identical though the trends followed are the same. For example, for the individual blockages in the left common carotid (Fig A-2), left vertebral (Fig A-7) and the left internal carotid (Fig A-9), the trend followed by the figures for the cerebral blood flow is almost identical to that followed by their counterparts on the right side (Figures A-4, A-6 and A-8). The small deviation in the

absolute figures is only because of the geometric location of each of the arteries.

The blocking of the brachiocephalic (Fig A-1) results in a very sharp reduction of flow to the brain because this artery is indirectly responsible to supply blood to the brain through the right internal carotid and the right vertebral. A complete blockage of this artery theoretically means paralysis of the upper right extremities, including the arm, together with no feeding of the brain from the right side. The arteries on the left side which are responsible to meet the partial requirements of the brain tend to take up the slack because of a higher pressure drifting towards them. As a result, these arteries start discharging blood more than their normal capacity though still unable to meet the flow requirements of the brain completely. In many cases, it has been practically observed that even when the subclavians are not receiving any blood through the direct route, the arms keep on receiving a minimal portion of their blood requirement due to a reversed flow in the vertebrals. The blood that reaches the brain, though not sufficient for the brain itself, travels through the complex circle of Willis in the upper part and finds its way to the vertebral that is not supplying any blood to the brain because of a complete blockage of either the brachiocephalic or one of the subclavians. Therefore, in such cases, the subclavian is fed through the vertebral. An exact estimate of the flow through this indirect route has

not been determined in the present analysis because the complex path in the head was not modelled. However, for the reasons mentioned above, it is recommended that the figures for the cerebral blood flow, in the event of a blockage of the brachiocephalic or the subclavians, should be used with a tolerance to account for the physiological by-pass to the arms. This is particularly important when there is a more or less complete blockage of any of the three arteries mentioned above with the corresponding vertebral not badly affected by the disease i.e., when a paralysis of the arm or the face is not observed in a patient with severely blocked brachiocephalic or any of the subclavians.

In all the cases (Fig A-1 through A-9), an identical behaviour is observed in the sense that the points for 50 and 70 beats per minute (Average Reynolds Number=680 and 1000) are more close than those for 70 and 90 beats per minute (Average Reynolds Number=1000 and 1300). This shows that for lower Reynolds number the percentage of blood flowing towards the upper extremities is comparatively higher than that at larger Reynolds numbers. This fact is phenomenally pronounced in the case of complete blockage of the brachiocephalic when the flow to the brain hardly changes as the pulse rate falls from 70 to 50. The inertia of the flowing fluid explains this behaviour very clearly.

Figures A-10 through A-29 shows the cerebral blood flow for various cases of atherosclerosis under varying heart rate. The cases represent several mild and severe stages of

the disease as described in Table A-1.

In some combinations, for example, in case of a single 50% blockage of the left vertebral (case 33), the reduction in the cerebral blood flow at normal pulse rate is very minimal and almost of no concern from the surgical point of view. Since the present analysis concentrates more on the blood reaching the brain, the most severe case of arterial stenosis studied was when a complete blockage of the left and right common carotids was represented (case 20). In this case the cerebral blood flow stays below 50% of the normal figure even when the pulse rate jumps to 90. Under these conditions, not considering the facial paralysis, a permanent damage of the brain is inevitable. However, the information can be helpful in surgery if it requires a temporary blockage of these arteries in the above pattern. Similarly, in cases 7 and 21, which represent the disease to the degree of comparatively less severity, the blood flow to the brain is below the 50% level at the normal pulse rate. In cases 23, 57 and 60 the same flow is on or just above the critical 50% value but falls below when the heart rate drops. In these cases once again, the brain is prone to an irreversible damage.

A surgical treatment is normally considered when the lumen of an artery reduces by 50% or more. In that case, during the period of the surgery, the particular artery has to be completely blocked which implies a complete shut down of blood supply through that artery for a short duration.

In some cases, this can reduce the flow below a critical value (determined by the surgeons) resulting in a permanent damage to the organ supplied, if a temporary by-pass is not provided or, in some cases, if the proper sequence of treatment is not followed. In other words, in support of a decision for the surgical treatment of an artery, the surgeon has to have some pre-surgical information regarding the flow distribution prior to and during the course of the surgery. The results as given in Appendix A can be applied directly in such cases. For example, among the cases studied, if a surgical treatment of the 75% blocked common carotid is recommended in case 21 or case 23, in the event of no by-pass it would represent case 20 during the course of surgery and this case has already been determined as a very severe case theoretically representing no survival. Therefore, the surgery, if carried out without a by-pass will not be successful. Similarly, in case 5 or case 6, if the left common carotid is blocked for surgical treatment, the cerebral blood flow would reduce considerably to damage the brain if a temporary by-pass is not provided. This may also suggest that the completely blocked artery be treated first, for reasons mentioned later. In case 16, for a similar treatment of the left common carotid, the cerebral flow would fall very close to the 50% level which will be very much susceptible to fall further below if the normal heart rate is not maintained during the surgery. This is true even when it is assumed that a part of the slack would

be taken up by the other three arteries feeding the brain.

The cerebral blood flow in case 18, which represents a completely blocked brachiocephalic, is far below normal but not critical from the surgical point of view if the patient is already surviving. A similar conclusion can be drawn for other cases which involve a complete blockage of one or more arteries. This implies that for the surgical treatment of a completely blocked artery of a surviving patient, the by-pass may not be required during the period of the surgery. However, a clear and more detailed analysis for recommendation of a by-pass is possible only after a mathematical model is built on the present information so that the data could be interpolated and analysed for an infinite combination of diseased arteries.

An interesting observation is made in the case of a 50% blockage of the left vertebral (case 33) which hardly effects the flow to the brain at the normal pulse rate. This observation is further confirmed by comparing cases 37 and 38 which give almost the same figures for the cerebral blood flow. The slight decrease in the flow through the left vertebral due to the blockage is taken up by the other arteries feeding the brain. However, any constriction in its counterpart on the right side do not produce an identical effect and reduces the flow though not by a considerably large amount. This difference in the behaviour of the two vertebrals can once again be explained considering the variations in the geometry on the two sides

of the arterial system under investigation.

Since the cardiac output remains almost the same regardless of the blockages introduced in one or more of the branches, any reduction in flow through these has to be taken up by the other arteries. This does not only mean that other parts of the body are receiving more blood than their normal requirements but also that the other arteries are carrying blood more than their normal capacities and, therefore, are under some kind of undesirable additional stresses. In some cases, this effect can become severe enough to cause haemmorhage. In other words, a lack of blood supply is not the only reason to call for a surgery. The results given in Appendix A give a complete flow distribution in the main branches and can, therefore, also be used for other considerations.

A few cases representing entirely different combinations of blockages have been observed to produce a more or less identical effect on the cerebral blood flow. For example, a 75% blockage of brachiocephalic together with a 50% blockage in the left common carotid (case 8) and a 50% blockage in each of the right vertebral, left vertebral, right internal carotid and the left internal carotid (case 30) result in same flow to the brain at the normal pulse rate of 70 though both these cases represent the disease in an entirely different form. As another example, a similar effect is also observed in cases when the left common carotid and the left subclavian has a 75% blockage each

(case 13) and the right internal carotid has a 75% blockage (case 55). This shows that for a particular flow to the brain there is not necessarily only one combination of arterial stenosis; various diseased arteries may produce the same effect on the total volume of blood reaching the brain.

GLOSSARY

Angiography: Determination of the state and arrangement of blood or lymph vessels without dissection, as by radiography.

Arteriosclerosis: A condition marked by loss of elasticity, thickening and hardening of the arteries.

Atherosclerosis: A lesion of large and medium-sized arteries, with deposits in the intima of yellowish plaques containing cholestrol, lipoid material, etc.

Brachiocephalic: Pertaining to the arm and head.

Circle of Willis: The arterial circle of the cerebrum.

Common Carotid: An artery that originates on the right from the brachiocephalic trunk and on the left from the arch of the aorta; it divides into the internal and external carotids and distributes blood to the region of the neck and head.

Diastole: The rhythmic period of relaxation and dilatation of a chamber of the heart during which it fills with blood.

Diastolic pressure: Minimum blood pressure during ventricular diastole.

Endothelium: The simple epithelium lining of the heart, blood vessels and lymph vessels.

Epithelium: A tissue composed of contiguous cells with a minimum of intercellular substance.

Etiologic: The science or study of the causes of disease, both direct and predisposing, and the mode of their operation.

Iliacs: Pertaining to the flanks or the superior broad portion of the hipbone.

Intercostal: Situated between the ribs.

Intima: The innermost of the three coats of a blood vessel.

Lumen: The space inside of a tube.

Renal: Pertaining to the kidney.

Occlusion: The state of being closed or shut.

Stenosis: Constriction or narrowing, especially of a lumen or orifice.

Subclavian: Lying under the clavicle.

Systole: The contraction phase of the cardiac cycle.

REFERENCES

ALBRITTON E.C., editor: **Standard Values in Blood;** Phil:W.B.Saunders Co., 1952.

ANLIKER M., STETTLER J.C., NIEDERER P., HOLENSTEIN R.: **Prediction of Shape Changes of Propagating Flow and Pressure Pulses in Human Arteries;** presented at Int'l Symp. on "Dynamics and Regulation of The Arterial System", Erlangen, Germany, Oct 28-30, 1977.

ANSON B.J.,editor: **Morris' Human Anatomy;** McGraw Hill Book Co., 1966.

BALASUBRAMANIAM K., GIDDENS D.P., MABON R.F.: **Steady Flow at The Carotid Bifurcation;** presented at The Second Mid-Atlantic Conference on Bio-Fluid Mechanics held at Va. Poly. Inst. & State Univ., Blacksburg, VA, May 5-7, 1980.

CARO C.G., PEDLEY T.J., SCHROTER R.C., SEED W.A.: **The Mechanics of Circulation;** Oxford University Press, Oxford, 1978.

DAVIS D.V., editor: **Gray's Anatomy...Descriptive and Applied, 34th ed.;** Longmans Green & Co. Ltd., London, 1967.

DeGARIS C.F., BLACK I.H. & RIEMENSCHNEIDER E.A.: **Patterns of the aortic arch in American white and Negro stocks;** J. Anat. 67:599-617, July 1933.

FURUKAWA K., YOSHIKAWA J., TANAKA K., TANAKA C., KAWAI S., TAKEUCHI K. & SHIOTA K.: **Echocardiographic Measurements of Aortic Root Diameter;** Japanese Heart Journal, vol 17, No.4, July 1976.

GUYTON A.C.: **Textbook of Medical Physiology;** W.B.Saunders Co., Phil. & London, 1966.

HAUST M.D.: **Arterial Endothelium and its Potentials;** Atherosclerosis:Metabolic, Morphologic and Clinical Aspects, edited by Manning G.W., Haust M.D., pp 34-39, New York:Plenum Press, 1976.

HOLE J.W. JR: **Human Anatomy and Physiology;** Wm. C. Brown Co. Publ., Iowa, 1978.

IMPARATO A.M., LORD J.W., TEXON M., HELPERN M.: **Experimental Atherosclerosis produced by Alteration of Blood Vessel Configuration;** Surg. Forum., 12:245, 1961.

JENNINGS R. & SIDWELL E.H.: **Graphics for Engineers;** Edward Arnold (Publishers) Ltd. London, 1968.

JENSEN P.W.: **Cam Design and Manufacture;** The Industrial Press, New York, 1965.

LUSTED L.B. & KEATS T.E.: **An Atlas of Roentgenographic Measurement, 4th ed.;** Yearbook Medical Publishers Inc., Chicago, 1978.

McDONALD D.A.: **Blood Flow in Arteries;** Edward Arnold (Publishers) Ltd., London, 1974.

McDONALD J.J. & ANSON B.J.: **Variations in the origin of arteries derived from the aortic arch, in American whites and Negroes;** Am. J. of Phys. Anthropol. 27:91-107, June 1940.

MESCHAN I.: **An Atlas of Anatomy Basic to Radiology;** W.B.Saunders Co., Phil., 1975.

MIDDLEMAN S.: **Transport Phenomenon in the Cardiovascular System;** Wiley-Interscience, 1972.

NATHANIEL E. REICH: **Diseases of the Aorta...Diagnosis and Treatment;** The Macmillan Co., NY, 1949.

PHILIP L. ALTMAN & DOROTHY S. DITTMER, editor: **Respiration and Circulation;** Fed. of Amer. Soc. for Experimental Biol., MD, 1971.

REUL H., TESCH B., SCHOENMAKERS J. and EFFERT S.: A Hydrodynamic Model of Left Ventricle, Aorta and its Branches; Basic Research in Cardiology, vol 69, No.3, May 1974.

RODKIEWICZ C.M., ZAJAC S., JEDRUCH W.T., HSIEH W.T.M.: Effect of Aortic Arch Atherosclerotic Formations on Blood Mass Flow Distribution; J. of Biomedical Engg., vol 101, 1979.

RODKIEWICZ C.M.: Localization of early Atherosclerotic Lesions in the Aortic Arch in the light of Fluid Flow; J. Biomechanics, vol 8, pp 149-156, 1975.

ROSENBLATT G., STOKES J.,BASSETT D.R.: Whole Blood Viscosity, Hematocrit, and Serum Lipid Levels in Normal Subjects and Patients with Coronary Heart Disease; J. Lab. and Clin. Med., vol 65, pp 202-211, 1965.

ROTHBART H.A.: Cams...Design, Dynamics and Accuracy; John Wiley & Sons Inc., New York, 1968.

SCHOTTELIUS & SCHOTTELIUS: Textbook of Physiology; The C.V. Mosby Co., St. Louis, 1978.

SYNDER M.F., RIDEOUT V.C., HILLESTAD R.J.: Computer Modelling of The Human Systemic Arterial Tree; J. Biomech. 1:341-353, 1968.

TEXON M.: Hemodynamic Basis of Atherosclerosis; Hemisphere Publishing Corp., New York, 1980.

TEXON M., IMPARATO A.M., LORD J.W.: Hemodynamic concept of Atherosclerosis...Experimental production of of Arterial Wall Lesions; A.M.A. Arch. Surg. 80:47, 1960.

WHITBY L.E.H. & BRITTON C.J.C.: Disorders of the Blood; Phil:P. Blakiston's Son & Co. Inc., 1950.

WHITMORE R.L.: Rheology of the Circulation; Pergamon Press, 1968.

WIETING D.W.: A Method for Analyzing the Dynamic Flow Characteristics of Prosthetic Heart Valves; ASME paper No. 68-WA/BHF-3, 1968.

WINTROBE M.M.: Clinical Hematology; Lea & Febiger, 1967.

APPENDIX A

EXPERIMENTAL RESULTS

TABLE A-1 .. DESCRIPTION OF BLOCKAGES

CASE NUMBER	BRACHIO-CEPHALIC	L. COMMON CAROTID	LEFT SUBCLAVIAN	R. COMMON CAROTID	RIGHT SUBCLAVIAN	RIGHT VERTEBRAL	LEFT VERTEBRAL	R.INTERNAL CAROTID	L.INTERNAL CAROTID
1									
2		50%	50%						
3	50%	50%	50%						
4	50%								
5	50%	75%	100%						
6	75%	50%	100%						
7	100%	50%	75%						
8	75%	50%					50%		
9	75%	50%					75%		
10		50%	75%						
11		75%							
12		75%	50%						
13		75%	75%						
14			75%						
15	75%		75%						
16	75%	75%	75%						
17	75%								
18	100%								
19		100%							
20		100%		100%					

Continued

TABLE A-1 .. Continued

CASE NUMBER	BRACHIO-CEPHALIC	L. COMMON CAROTID	LEFT SUBCLAVIAN	R. COMMON CAROTID	RIGHT SUBCLAVIAN	RIGHT VERTEBRAL	LEFT VERTEBRAL	R.INTERNAL CAROTID	L.INTERNAL CAROTID
21		100%		75%					
22		50%		50%					
23		75%		100%					
24				75%					
25				100%		75%			
26				100%					
27				100%		50%			
28						50%		50%	
29						50%		50%	50%
30						50%	50%	50%	50%
31						50%	50%		
32							50%		50%
33							50%		
34						50%			50%
35						50%			
36								50%	50%
37							50%	50%	
38								50%	
39									50%
40				50%					

Continued

TABLE A-1 .. Continued

CASE NUMBER	BRACHIO-CEPHALIC	L. COMMON CAROTID	LEFT SUBCLAVIAN	R. COMMON CAROTID	RIGHT SUBCLAVIAN	RIGHT VERTEBRAL	LEFT VERTEBRAL	R.INTERNAL CAROTID	L.INTERNAL CAROTID
41		50%							
42	100%	50%							
43		50%		100%					
44		100%		50%					
45	100%		50%						
46		100%	50%						
47			50%	100%					
48							75%		
49						75%	75%		
50						75%			
51						75%			75%
52									75%
53							75%		75%
54							75%	75%	
55								75%	
56						75%		75%	
57							75%		100%
58									100%
59								100%	
60							100%	100%	

Continued

TABLE A-1 .. Continued

CASE NUMBER	BRACHIO-CEPHALIC	L. COMMON CAROTID	LEFT SUBCLAVIAN	R. COMMON CAROTID	RIGHT SUBCLAVIAN	RIGHT VERTEBRAL	LEFT VERTEBRAL	R.INTERNAL CAROTID	L.INTERNAL CAROTID
61							100%		
62						100%			
63					100%				
64					75%				
65					50%				
66			100%						
67			50%						

TABLE A-2 [1] .. REFERENCE FIGURES

Based on

UNSTEADINESS PARAMETER: 19.198

PULSE RATE: 70.000

AVERAGE REYNOLDS NUMBER: 1000

CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
0.229	0.170	0.113	0.114	0.285	0.284	0.114	0.114	0.173	0.907	3.176	5.680	0.797
4.034%	2.999%	1.989%	2.016%	5.020%	5.009%	2.001%	2.013%	3.043%	15.967%	55.909%	100.000%	14.031%

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[1] 1st Row: Flow, litres/minute
2nd Row: % of the total flow

TABLE A-3 [1] .. FLOW DISTRIBUTION (AV REYNOLDS NO = 680)

UNSTEADINESS PARAMETER: 16.225

PULSE RATE: 50.000

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
1	0.183 3.230% -0.804	0.142 2.494% -0.505	0.075 1.323% -0.666	0.099 1.746% -0.270	0.240 4.234% -0.786	0.242 4.269% -0.739	0.099 1.743% -0.258	0.093 1.637% -0.376	0.155 2.735% -0.308	0.507 8.920% -7.048	2.067 36.383% -19.526	3.903 68.714% -31.286	0.651 11.464% -2.567
2	0.189 3.327% -0.707	0.146 2.575% -0.424	0.076 1.342% -0.647	0.101 1.782% -0.233	0.246 4.331% -0.690	0.227 4.001% -1.008	0.092 1.620% -0.381	0.091 1.606% -0.406	0.150 2.649% -0.393	0.515 9.066% -6.901	2.067 36.398% -19.512	3.902 68.698% -31.302	0.641 11.280% -2.751
3	0.189 3.336% -0.698	0.141 2.487% -0.512	0.076 1.334% -0.656	0.095 1.668% -0.348	0.229 4.031% -0.989	0.227 3.996% -1.012	0.092 1.615% -0.386	0.091 1.598% -0.415	0.150 2.645% -0.398	0.520 9.154% -6.813	2.097 36.926% -18.984	3.907 68.790% -31.210	0.622 10.959% -3.072
4	0.185 3.266% -0.769	0.136 2.399% -0.600	0.073 1.290% -0.700	0.096 1.699% -0.317	0.235 4.133% -0.888	0.245 4.322% -0.687	0.100 1.760% -0.241	0.095 1.672% -0.340	0.158 2.782% -0.261	0.512 9.022% -6.945	2.082 36.662% -19.248	3.920 69.006% -30.994	0.648 11.417% -2.614
5	0.220 3.873% -0.161	0.162 2.856% -0.142	0.084 1.483% -0.506	0.112 1.976% -0.040	0.266 4.683% -0.337	0.178 3.138% -1.870	0.075 1.320% -0.681	0.0 0.0 % -2.013	0.0 0.0 % -3.043	0.576 10.145% -5.823	2.240 39.434% -16.475	3.914 68.909% -31.091	0.528 9.304% -4.727
6	0.221 3.891% -0.144	0.132 2.328% -0.670	0.066 1.166% -0.823	0.094 1.659% -0.356	0.220 3.873% -1.147	0.260 4.582% -0.427	0.107 1.879% -0.122	0.0 0.0 % -2.013	0.0 0.0 % -3.043	0.580 10.211% -5.757	2.250 39.610% -16.299	3.931 69.199% -30.801	0.546 9.621% -4.410

Continued

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[1] 1st Row: Flow, litres/minute
2nd Row: % of the reference total flow as given in Table A-2
3rd Row: Deviation from normal flow (2nd row minus figures of Table A-2)
Description of Blockages for each case is given in Table A-1

TABLE A-3 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
7	0.264 4.643% 0.609	0.0 0.0 % -2.999	0.0 0.0 % -1.989	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.300 5.277% 0.268	0.126 2.223% 0.222	0.095 1.681% -0.332	0.155 2.729% -0.314	0.625 11.003% -4.964	2.342 41.239% -14.671	3.908 68.794% -31.206	0.395 6.958% -7.073
8	0.197 3.477% -0.557	0.114 2.011% -0.987	0.058 1.021% -0.968	0.080 1.408% -0.607	0.197 3.468% -1.552	0.234 4.128% -0.880	0.095 1.668% -0.333	0.083 1.457% -0.556	0.161 2.830% -0.213	0.539 9.484% -6.483	2.155 37.938% -17.971	3.913 68.891% -31.109	0.572 10.074% -3.957
9	0.199 3.512% -0.522	0.115 2.029% -0.970	0.059 1.047% -0.942	0.082 1.439% -0.577	0.199 3.512% -1.508	0.235 4.146% -0.863	0.095 1.677% -0.324	0.060 1.052% -0.961	0.161 2.843% -0.200	0.548 9.639% -6.329	2.150 37.850% -18.059	3.905 68.746% -31.254	0.554 9.757% -4.274
10	0.190 3.340% -0.694	0.146 2.575% -0.424	0.074 1.298% -0.691	0.100 1.760% -0.255	0.245 4.309% -0.712	0.225 3.970% -1.039	0.093 1.637% -0.364	0.073 1.285% -0.728	0.119 2.104% -0.939	0.511 9.000% -6.967	2.102 37.014% -18.896	3.879 68.293% -31.707	0.617 10.862% -3.169
11	0.192 3.371% -0.663	0.146 2.579% -0.420	0.078 1.373% -0.616	0.100 1.756% -0.260	0.244 4.304% -0.716	0.155 2.720% -2.289	0.066 1.162% -0.839	0.096 1.690% -0.323	0.157 2.760% -0.283	0.531 9.352% -6.615	2.150 37.850% -18.059	3.915 68.918% -31.082	0.573 10.087% -3.943
12	0.192 3.376% -0.659	0.147 2.597% -0.402	0.079 1.386% -0.603	0.100 1.765% -0.251	0.246 4.340% -0.681	0.157 2.760% -2.249	0.066 1.158% -0.844	0.093 1.646% -0.367	0.150 2.641% -0.402	0.530 9.330% -6.637	2.150 37.850% -18.059	3.911 68.847% -31.153	0.575 10.131% -3.899
13	0.198 3.486% -0.549	0.151 2.654% -0.345	0.080 1.408% -0.581	0.103 1.813% -0.202	0.252 4.432% -0.588	0.160 2.812% -2.196	0.067 1.188% -0.813	0.074 1.303% -0.710	0.121 2.135% -0.908	0.545 9.595% -6.373	2.182 38.422% -17.487	3.933 69.248% -30.752	0.565 9.955% -4.075
14	0.189 3.323% -0.712	0.146 2.570% -0.428	0.079 1.386% -0.603	0.100 1.756% -0.260	0.244 4.300% -0.720	0.244 4.304% -0.704	0.100 1.752% -0.249	0.072 1.276% -0.736	0.118 2.086% -0.957	0.509 8.956% -7.011	2.108 37.102% -18.808	3.909 68.812% -31.188	0.640 11.267% -2.764

Continued

TABLE A-3 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.196	0.108	0.058	0.090	0.216	0.254	0.102	0.073	0.122	0.530	2.153	3.901	0.601
15	3.446%	1.901%	1.012%	1.580%	3.811%	4.467%	1.796%	1.294%	2.148%	9.330%	37.894%	68.680%	10.585%
	-0.588	-1.097	-0.977	-0.436	-1.209	-0.541	-0.205	-0.719	-0.895	-6.637	-18.015	-31.320	-3.446
	0.204	0.111	0.058	0.091	0.222	0.168	0.071	0.075	0.124	0.561	2.250	3.936	0.523
16	3.600%	1.950%	1.012%	1.606%	3.913%	2.958%	1.246%	1.320%	2.192%	9.881%	39.610%	69.287%	9.203%
	-0.434	-1.049	-0.977	-0.409	-1.108	-2.051	-0.756	-0.692	-0.851	-6.087	-16.299	-30.713	-4.828
	0.189	0.104	0.054	0.087	0.208	0.246	0.100	0.095	0.156	0.515	2.108	3.862	0.604
17	3.327%	1.826%	0.959%	1.536%	3.662%	4.331%	1.760%	1.677%	2.746%	9.066%	37.102%	67.993%	10.629%
	-0.707	-1.172	-1.030	-0.480	-1.358	-0.678	-0.241	-0.336	-0.296	-6.901	-18.808	-32.007	-3.402
	0.252	0.0	0.0	0.0	0.0	0.311	0.131	0.121	0.196	0.611	2.305	3.928	0.433
18	4.436%	0.0 %	0.0 %	0.0 %	0.0 %	5.479%	2.306%	2.139%	3.446%	10.761%	40.579%	69.146%	7.618%
	0.402	-2.999	-1.989	-2.016	-5.020	0.471	0.305	0.126	0.403	-5.207	-15.331	-30.854	-6.412
	0.214	0.168	0.081	0.115	0.273	0.0	0.0	0.106	0.174	0.565	2.225	3.921	0.460
19	3.772%	2.958%	1.426%	2.020%	4.802%	0.0 %	0.0 %	1.866%	3.072%	9.947%	39.170%	69.032%	8.094%
	-0.263	-0.041	-0.563	0.004	-0.219	-5.009	-2.001	-0.147	0.029	-6.021	-16.739	-30.968	-5.937
	0.255	0.206	0.104	0.0	0.0	0.0	0.0	0.124	0.197	0.644	2.395	3.925	0.228
20	4.498%	3.631%	1.840%	0.0 %	0.0 %	0.0 %	0.0 %	2.179%	3.459%	11.333%	42.163%	69.102%	4.018%
	0.464	0.632	-0.150	-2.016	-5.020	-5.009	-2.001	0.166	0.417	-4.634	-13.746	-30.898	-10.013
	0.224	0.169	0.084	0.075	0.173	0.0	0.0	0.108	0.177	0.592	2.287	3.892	0.366
21	3.943%	2.980%	1.488%	1.320%	3.050%	0.0 %	0.0 %	1.910%	3.120%	10.431%	40.271%	68.513%	6.448%
	-0.091	-0.019	-0.502	-0.695	-1.970	-5.009	-2.001	-0.103	0.078	-5.537	-15.639	-31.487	-7.583
	0.186	0.140	0.072	0.089	0.219	0.223	0.090	0.094	0.155	0.506	2.090	3.866	0.608
22	3.274%	2.469%	1.268%	1.571%	3.855%	3.935%	1.593%	1.655%	2.729%	8.912%	36.794%	68.055%	10.712%
	-0.760	-0.530	-0.722	-0.445	-1.165	-1.074	-0.408	-0.358	-0.314	-7.055	-19.116	-31.945	-3.318

Continued

TABLE A-3 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.224	0.180	0.090	0.0	0.0	0.181	0.078	0.107	0.176	0.582	2.282	3.901	0.379
23	3.943%	3.164%	1.593%	0.0 %	0.0 %	3.186%	1.369%	1.888%	3.103%	10.255%	40.183%	68.684%	6.668%
	-0.091	0.166	-0.396	-2.016	-5.020	-1.822	-0.632	-0.125	0.060	-5.713	-15.727	-31.316	-7.363
	0.191	0.143	0.072	0.063	0.150	0.249	0.100	0.095	0.158	0.528	2.150	3.898	0.566
24	3.367%	2.513%	1.268%	1.105%	2.636%	4.388%	1.765%	1.677%	2.777%	9.286%	37.850%	68.632%	9.969%
	-0.668	-0.486	-0.722	-0.911	-2.384	-0.621	-0.236	-0.336	-0.266	-6.681	-18.059	-31.368	-4.062
	0.216	0.177	0.054	0.0	0.0	0.279	0.115	0.105	0.174	0.560	2.190	3.870	0.438
25	3.807%	3.116%	0.951%	0.0 %	0.0 %	4.912%	2.025%	1.848%	3.059%	9.859%	38.554%	68.130%	7.711%
	-0.227	0.117	-1.039	-2.016	-5.020	-0.097	0.023	-0.164	0.016	-6.109	-17.355	-31.870	-6.320
	0.215	0.174	0.090	0.0	0.0	0.275	0.114	0.105	0.171	0.561	2.202	3.909	0.470
26	3.776%	3.072%	1.580%	0.0 %	0.0 %	4.841%	2.016%	1.857%	3.019%	9.881%	38.774%	68.816%	8.279%
	-0.258	0.073	-0.409	-2.016	-5.020	-0.167	0.015	-0.156	-0.023	-6.087	-17.135	-31.184	-5.752
	0.213	0.174	0.085	0.0	0.0	0.275	0.113	0.104	0.170	0.555	2.193	3.883	0.464
27	3.754%	3.068%	1.501%	0.0 %	0.0 %	4.837%	1.994%	1.835%	3.002%	9.771%	38.598%	68.359%	8.173%
	-0.280	0.069	-0.489	-2.016	-5.020	-0.172	-0.007	-0.178	-0.041	-6.197	-17.311	-31.641	-5.858
	0.185	0.143	0.069	0.099	0.179	0.244	0.099	0.092	0.153	0.516	2.102	3.882	0.585
28	3.257%	2.522%	1.224%	1.743%	3.160%	4.291%	1.743%	1.620%	2.689%	9.088%	37.014%	68.350%	10.294%
	-0.778	-0.477	-0.766	-0.273	-1.860	-0.717	-0.258	-0.393	-0.354	-6.879	-18.896	-31.650	-3.737
	0.181	0.137	0.067	0.092	0.192	0.201	0.095	0.095	0.149	0.520	2.170	3.900	0.556
29	3.195%	2.407%	1.188%	1.620%	3.380%	3.547%	1.681%	1.672%	2.619%	9.154%	38.202%	68.667%	9.788%
	-0.839	-0.591	-0.801	-0.396	-1.640	-1.461	-0.320	-0.340	-0.424	-6.813	-17.707	-31.333	-4.243
	0.181	0.137	0.068	0.092	0.190	0.201	0.096	0.087	0.148	0.520	2.153	3.873	0.546
30	3.186%	2.412%	1.197%	1.615%	3.354%	3.534%	1.690%	1.532%	2.610%	9.154%	37.894%	68.178%	9.617%
	-0.848	-0.587	-0.792	-0.401	-1.667	-1.474	-0.311	-0.481	-0.433	-6.813	-18.015	-31.822	-4.414

Continued

TABLE A-3 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.177	0.137	0.069	0.094	0.247	0.246	0.095	0.088	0.149	0.497	2.097	3.899	0.650
31	3.125%	2.421%	1.215%	1.655%	4.344%	4.340%	1.681%	1.545%	2.627%	8.758%	36.926%	68.636%	11.443%
	-0.910	-0.578	-0.775	-0.361	-0.676	-0.669	-0.320	-0.468	-0.415	-7.209	-18.984	-31.364	-2.588
	0.178	0.137	0.073	0.093	0.247	0.199	0.096	0.087	0.148	0.510	2.142	3.910	0.606
32	3.129%	2.403%	1.281%	1.637%	4.353%	3.503%	1.690%	1.536%	2.610%	8.978%	37.718%	68.838%	10.673%
	-0.905	-0.596	-0.709	-0.378	-0.668	-1.505	-0.311	-0.477	-0.433	-6.989	-18.191	-31.162	-3.358
	0.178	0.137	0.074	0.094	0.248	0.247	0.095	0.087	0.149	0.500	2.105	3.914	0.655
33	3.138%	2.407%	1.298%	1.655%	4.357%	4.348%	1.681%	1.536%	2.632%	8.802%	37.058%	68.913%	11.540%
	-0.896	-0.591	-0.691	-0.361	-0.663	-0.660	-0.320	-0.477	-0.411	-7.165	-18.852	-31.087	-2.491
	0.177	0.137	0.068	0.093	0.246	0.199	0.096	0.090	0.149	0.505	2.132	3.892	0.603
34	3.120%	2.407%	1.202%	1.633%	4.331%	3.499%	1.690%	1.593%	2.619%	8.890%	37.542%	68.526%	10.624%
	-0.914	-0.591	-0.788	-0.383	-0.690	-1.510	-0.311	-0.420	-0.424	-7.077	-18.367	-31.474	-3.406
	0.176	0.136	0.068	0.094	0.243	0.244	0.092	0.087	0.147	0.500	2.100	3.887	0.642
35	3.103%	2.390%	1.202%	1.650%	4.274%	4.296%	1.620%	1.540%	2.588%	8.802%	36.970%	68.433%	11.311%
	-0.932	-0.609	-0.788	-0.365	-0.747	-0.713	-0.381	-0.472	-0.455	-7.165	-18.940	-31.567	-2.720
	0.179	0.137	0.074	0.091	0.196	0.198	0.096	0.090	0.148	0.523	2.180	3.912	0.558
36	3.160%	2.403%	1.307%	1.611%	3.451%	3.486%	1.690%	1.576%	2.614%	9.198%	38.378%	68.874%	9.819%
	-0.874	-0.596	-0.682	-0.405	-1.570	-1.523	-0.311	-0.437	-0.428	-6.769	-17.531	-31.126	-4.212
	0.178	0.137	0.074	0.092	0.197	0.247	0.093	0.086	0.147	0.505	2.135	3.891	0.604
37	3.129%	2.407%	1.307%	1.624%	3.464%	4.344%	1.642%	1.518%	2.597%	8.890%	37.586%	68.508%	10.633%
	-0.905	-0.591	-0.682	-0.392	-1.557	-0.665	-0.359	-0.494	-0.446	-7.077	-18.323	-31.492	-3.398
	0.176	0.137	0.073	0.091	0.196	0.245	0.092	0.089	0.149	0.508	2.135	3.893	0.604
38	3.107%	2.403%	1.294%	1.611%	3.455%	4.322%	1.628%	1.571%	2.623%	8.934%	37.586%	68.535%	10.642%
	-0.927	-0.596	-0.695	-0.405	-1.565	-0.687	-0.373	-0.442	-0.420	-7.033	-18.323	-31.465	-3.389

Continued

TABLE A-3 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.177	0.136	0.069	0.092	0.245	0.198	0.096	0.090	0.149	0.508	2.130	3.890	0.602
39	3.116%	2.394%	1.215%	1.628%	4.313%	3.486%	1.690%	1.589%	2.623%	8.934%	37.498%	68.486%	10.602%
	-0.918	-0.604	-0.775	-0.387	-0.707	-1.523	-0.311	-0.424	-0.420	-7.033	-18.411	-31.514	-3.428
	0.185	0.139	0.071	0.089	0.216	0.241	0.099	0.092	0.152	0.505	2.085	3.875	0.621
40	3.252%	2.456%	1.254%	1.562%	3.807%	4.252%	1.738%	1.620%	2.680%	8.890%	36.706%	68.218%	10.932%
	-0.782	-0.543	-0.735	-0.453	-1.213	-0.757	-0.263	-0.393	-0.362	-7.077	-19.204	-31.782	-3.098
	0.185	0.142	0.072	0.098	0.240	0.221	0.090	0.094	0.154	0.510	2.087	3.892	0.626
41	3.252%	2.500%	1.259%	1.725%	4.221%	3.891%	1.584%	1.655%	2.711%	8.978%	36.750%	68.526%	11.025%
	-0.782	-0.499	-0.731	-0.290	-0.800	-1.118	-0.417	-0.358	-0.332	-6.989	-19.160	-31.474	-3.006
	0.252	0.0	0.0	0.0	0.0	0.289	0.121	0.121	0.194	0.616	2.295	3.889	0.410
42	4.441%	0.0 %	0.0 %	0.0 %	0.0 %	5.092%	2.139%	2.130%	3.415%	10.849%	40.403%	68.469%	7.222%
	0.406	-2.999	-1.989	-2.016	-5.020	0.084	0.138	0.117	0.373	-5.119	-15.507	-31.531	-6.809
	0.215	0.175	0.086	0.0	0.0	0.253	0.105	0.106	0.173	0.570	2.202	3.885	0.444
43	3.785%	3.090%	1.510%	0.0 %	0.0 %	4.450%	1.848%	1.866%	3.046%	10.035%	38.774%	68.403%	7.825%
	-0.249	0.091	-0.480	-2.016	-5.020	-0.559	-0.153	-0.147	0.003	-5.933	-17.135	-31.597	-6.206
	0.215	0.165	0.082	0.104	0.249	0.0	0.0	0.105	0.174	0.559	2.200	3.854	0.436
44	3.794%	2.909%	1.439%	1.840%	4.384%	0.0 %	0.0 %	1.853%	3.068%	9.837%	38.730%	67.853%	7.676%
	-0.241	-0.089	-0.550	-0.176	-0.637	-5.009	-2.001	-0.160	0.025	-6.131	-17.179	-32.147	-6.355
	0.251	0.0	0.0	0.0	0.0	0.309	0.130	0.115	0.185	0.600	2.280	3.870	0.424
45	4.423%	0.0 %	0.0 %	0.0 %	0.0 %	5.440%	2.289%	2.025%	3.252%	10.563%	40.139%	68.130%	7.464%
	0.389	-2.999	-1.989	-2.016	-5.020	0.431	0.288	0.012	0.210	-5.405	-15.771	-31.870	-6.567
	0.214	0.168	0.084	0.114	0.271	0.0	0.0	0.100	0.164	0.550	2.216	3.883	0.455
46	3.776%	2.953%	1.483%	2.016%	4.766%	0.0 %	0.0 %	1.769%	2.896%	9.683%	39.016%	68.359%	8.019%
	-0.258	-0.045	-0.506	0.0	-0.254	-5.009	-2.001	-0.244	-0.147	-6.285	-16.893	-31.641	-6.012

Continued

TABLE A-3 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
47	0.215 3.776% -0.258	0.175 3.081% 0.082	0.088 1.554% -0.436	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.276 4.854% -0.154	0.113 1.998% -0.003	0.100 1.769% -0.244	0.164 2.892% -0.151	0.557 9.815% -6.153	2.207 38.862% -17.047	3.897 68.601% -31.399	0.464 8.177% -5.854
48	0.188 3.318% -0.716	0.146 2.570% -0.428	0.075 1.320% -0.669	0.101 1.787% -0.229	0.246 4.340% -0.681	0.246 4.340% -0.669	0.100 1.760% -0.241	0.053 0.929% -1.084	0.157 2.764% -0.279	0.512 9.022% -6.945	2.085 36.706% -19.204	3.911 68.856% -31.144	0.621 10.928% -3.103
49	0.190 3.345% -0.690	0.150 2.632% -0.367	0.045 0.792% -1.197	0.102 1.791% -0.224	0.250 4.397% -0.623	0.250 4.397% -0.612	0.100 1.765% -0.236	0.053 0.924% -1.089	0.160 2.817% -0.226	0.525 9.242% -6.725	2.092 36.838% -19.072	3.916 68.940% -31.060	0.597 10.510% -3.521
50	0.190 3.340% -0.694	0.147 2.592% -0.406	0.044 0.775% -1.215	0.101 1.778% -0.238	0.247 4.348% -0.672	0.248 4.357% -0.651	0.100 1.760% -0.241	0.093 1.637% -0.376	0.156 2.746% -0.296	0.515 9.066% -6.901	2.095 36.882% -19.028	3.935 69.283% -30.717	0.631 11.117% -2.914
51	0.192 3.380% -0.654	0.147 2.588% -0.411	0.042 0.748% -1.241	0.100 1.769% -0.246	0.249 4.379% -0.641	0.127 2.236% -2.773	0.104 1.831% -0.170	0.093 1.646% -0.367	0.156 2.755% -0.288	0.545 9.595% -6.373	2.180 38.378% -17.531	3.937 69.305% -30.695	0.512 9.009% -5.022
52	0.187 3.292% -0.742	0.140 2.473% -0.525	0.077 1.351% -0.638	0.098 1.721% -0.295	0.244 4.296% -0.725	0.124 2.192% -2.817	0.100 1.760% -0.241	0.090 1.589% -0.424	0.153 2.694% -0.349	0.529 9.308% -6.659	2.137 37.630% -18.279	3.880 68.306% -31.694	0.535 9.427% -4.604
53	0.189 3.323% -0.712	0.143 2.526% -0.472	0.078 1.369% -0.621	0.100 1.752% -0.264	0.248 4.357% -0.663	0.125 2.201% -2.808	0.101 1.782% -0.219	0.051 0.907% -1.106	0.153 2.702% -0.340	0.537 9.462% -6.505	2.140 37.674% -18.235	3.866 68.055% -31.945	0.502 8.833% -5.198
54	0.189 3.336% -0.698	0.146 2.575% -0.424	0.079 1.391% -0.599	0.101 1.778% -0.238	0.121 2.130% -2.890	0.249 4.392% -0.616	0.100 1.752% -0.249	0.055 0.959% -1.053	0.156 2.755% -0.288	0.543 9.551% -6.417	2.130 37.498% -18.411	3.869 68.117% -31.883	0.504 8.873% -5.158

Continued

TABLE A-3 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.188	0.145	0.078	0.100	0.124	0.245	0.100	0.095	0.154	0.534	2.153	3.914	0.541
55	3.314%	2.548%	1.369%	1.760%	2.187%	4.309%	1.752%	1.664%	2.711%	9.396%	37.894%	68.904%	9.528%
	-0.720	-0.450	-0.621	-0.255	-2.833	-0.700	-0.249	-0.349	-0.332	-6.571	-18.015	-31.096	-4.502
	0.189	0.148	0.044	0.101	0.118	0.246	0.100	0.094	0.155	0.530	2.150	3.875	0.503
56	3.336%	2.601%	0.783%	1.778%	2.069%	4.340%	1.752%	1.659%	2.729%	9.330%	37.850%	68.227%	8.851%
	-0.698	-0.398	-1.206	-0.238	-2.952	-0.669	-0.249	-0.354	-0.314	-6.637	-18.059	-31.773	-5.180
	0.201	0.154	0.082	0.106	0.261	0.0	0.114	0.055	0.161	0.561	2.200	3.896	0.397
57	3.547%	2.716%	1.444%	1.866%	4.595%	0.0 %	2.016%	0.959%	2.843%	9.881%	38.730%	68.596%	6.998%
	-0.487	-0.283	-0.546	-0.150	-0.425	-5.009	0.015	-1.053	-0.200	-6.087	-17.179	-31.404	-7.033
	0.201	0.155	0.080	0.105	0.257	0.0	0.114	0.100	0.164	0.554	2.202	3.932	0.437
58	3.530%	2.724%	1.408%	1.844%	4.524%	0.0 %	2.016%	1.769%	2.892%	9.749%	38.774%	69.230%	7.702%
	-0.505	-0.274	-0.581	-0.172	-0.496	-5.009	0.015	-0.244	-0.151	-6.219	-17.135	-30.770	-6.329
	0.199	0.159	0.081	0.121	0.0	0.259	0.105	0.100	0.162	0.548	2.197	3.931	0.440
59	3.512%	2.804%	1.430%	2.135%	0.0 %	4.560%	1.844%	1.756%	2.848%	9.639%	38.686%	69.212%	7.746%
	-0.522	-0.195	-0.559	0.119	-5.020	-0.449	-0.157	-0.257	-0.195	-6.329	-17.223	-30.788	-6.285
	0.208	0.168	0.086	0.128	0.0	0.269	0.110	0.0	0.173	0.555	2.197	3.894	0.355
60	3.666%	2.953%	1.518%	2.253%	0.0 %	4.736%	1.932%	0.0 %	3.046%	9.771%	38.686%	68.561%	6.254%
	-0.368	-0.045	-0.471	0.238	-5.020	-0 273	-0.069	-2.013	0.003	-6.197	-17.223	-31.439	-7.777
	0.193	0.150	0.078	0.103	0.250	0.251	0.102	0.0	0.163	0.515	2.115	3.920	0.578
61	3.402%	2.645%	1.369%	1.809%	4.397%	4.419%	1.804%	0.0 %	2.874%	9.066%	37.234%	69.019%	10.184%
	-0.632	-0.354	-0.621	-0.207	-0.623	-0.590	-0.197	-2.013	-0.169	-6.901	-18.676	-30.981	-3.847
	0.190	0.148	0.0	0.101	0.246	0.250	0.101	0.096	0.159	0.512	2.105	3.909	0.592
62	3.354%	2.601%	0.0 %	1.774%	4.331%	4.401%	1.782%	1.699%	2.795%	9.022%	37.058%	68.816%	10.431%
	-0.681	-0.398	-1.989	-0.242	-0.690	-0.607	-0.219	-0.314	-0.248	-6.945	-18.852	-31.184	-3.600

Continued

TABLE A-3 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.207	0.0	0.0	0.110	0.260	0.269	0.110	0.104	0.169	0.534	2.142	3.906	0.633
63	3.644%	0.0 %	0.0 %	1.932%	4.586%	4.731%	1.945%	1.835%	2.980%	9.396%	37.718%	68.768%	11.153%
	-0.390	-2.999	-1.989	-0.084	-0.434	-0.277	-0.056	-0.178	-0.063	-6.571	-18.191	-31.232	-2.878
	0.187	0.117	0.027	0.095	0.236	0.245	0.100	0.094	0.155	0.511	2.105	3.872	0.602
64	3.288%	2.060%	0.484%	1.668%	4.159%	4.313%	1.756%	1.650%	2.733%	9.000%	37.058%	68.169%	10.607%
	-0.747	-0.939	-1.505	-0.348	-0.861	-0.695	-0.245	-0.362	-0.310	-6.967	-18.852	-31.831	-3.424
	0.185	0.139	0.058	0.096	0.236	0.243	0.100	0.094	0.155	0.506	2.092	3.906	0.631
65	3.266%	2.456%	1.030%	1.690%	4.155%	4.274%	1.752%	1.659%	2.729%	8.912%	36.838%	68.759%	11.117%
	-0.769	-0.543	-0.959	-0.326	-0.866	-0.735	-0.249	-0.354	-0.314	-7.055	-19.072	-31.241	-2.914
	0.210	0.165	0.085	0.113	0.269	0.271	0.111	0.0	0.0	0.543	2.157	3.923	0.624
66	3.688%	2.900%	1.488%	1.998%	4.740%	4.766%	1.954%	0.0 %	0.0 %	9.551%	37.982%	69.067%	10.994%
	-0.346	-0.098	-0.502	-0.018	-0.280	-0.242	-0.047	-2.013	-3.043	-6.417	-17.927	-30.933	-3.037
	0.185	0.143	0.072	0.098	0.240	0.243	0.100	0.090	0.148	0.501	2.082	3.903	0.645
67	3.252%	2.522%	1.268%	1.730%	4.221%	4.287%	1.756%	1.584%	2.601%	8.824%	36.662%	68.706%	11.359%
	-0.782	-0.477	-0.722	-0.286	-0.800	-0.722	-0.245	-0.428	-0.442	-7.143	-19.248	-31.294	-2.671

TABLE A-4 [1] .. FLOW DISTRIBUTION (AV REYNOLDS NO = 1000)

UNSTEADINESS PARAMETER: 19.198

PULSE RATE: 70.000

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
1	0.229 4.034% -	0.170 2.999% -	0.113 1.989% -	0.114 2.016% -	0.285 5.020% -	0.284 5.009% -	0.114 2.001% -	0.114 2.013% -	0.173 3.043% -	0.907 15.967% -	3.176 55.909% -	5.680 100.000% -	0.797 14.031% -
2	0.230 4.053% 0.019	0.170 2.988% -0.010	0.113 1.985% -0.004	0.114 2.003% -0.013	0.286 5.035% 0.015	0.262 4.608% -0.401	0.102 1.796% -0.205	0.109 1.923% -0.089	0.165 2.914% -0.129	0.918 16.152% 0.185	3.205 56.423% 0.513	5.673 99.880% -0.120	0.770 13.551% -0.480
3	0.231 4.067% 0.032	0.167 2.940% -0.059	0.113 1.994% 0.004	0.105 1.844% -0.172	0.267 4.700% -0.320	0.262 4.612% -0.396	0.101 1.778% -0.223	0.109 1.923% -0.089	0.165 2.909% -0.134	0.925 16.284% 0.317	3.237 56.995% 1.086	5.683 100.047% 0.047	0.751 13.230% -0.801
4	0.231 4.062% 0.028	0.165 2.905% -0.094	0.093 1.637% -0.352	0.110 1.941% -0.075	0.277 4.885% -0.135	0.287 5.057% 0.048	0.112 1.981% -0.021	0.115 2.025% 0.012	0.175 3.090% 0.047	0.925 16.284% 0.317	3.250 57.215% 1.306	5.742 101.081% 1.081	0.773 13.604% -0.427
5	0.256 4.502% 0.468	0.169 2.975% -0.023	0.095 1.681% -0.308	0.106 1.870% -0.145	0.288 5.070% 0.050	0.181 3.182% -1.826	0.067 1.184% -0.817	0.0 0.0 % -2.013	0.0 0.0 % -3.043	1.009 17.759% 1.791	3.552 62.540% 6.631	5.724 100.764% 0.764	0.564 9.933% -4.097
6	0.259 4.568% 0.534	0.133 2.341% -0.657	0.074 1.307% -0.682	0.085 1.496% -0.519	0.233 4.111% -0.910	0.278 4.890% -0.119	0.102 1.804% -0.197	0.0 0.0 % -2.013	0.0 0.0 % -3.043	1.004 17.671% 1.703	3.550 62.496% 6.587	5.719 100.685% 0.685	0.585 10.307% -3.723

Continued

[1] 1st Row: Flow, litres/minute
2nd Row: % of the reference total flow as given in Table A-2
3rd Row: Deviation from normal flow (2nd row minus figures of Table A-2)
Description of Blockages for each case is given in Table A-1

TABLE A-4 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.273	0.0	0.0	0.0	0.0	0.291	0.104	0.087	0.130	1.050	3.755	5.690	0.378
7	4.810%	0.0 %	0.0 %	0.0 %	0.0 %	5.127%	1.822%	1.536%	2.289%	18.485%	66.105%	100.175%	6.663%
	0.776	-2.999	-1.989	-2.016	-5.020	0.119	-0.179	-0.477	-0.754	2.517	10.196	0.175	-7.368
	0.239	0.129	0.073	0.085	0.225	0.267	0.102	0.098	0.170	0.952	3.350	5.691	0.663
8	4.216%	2.275%	1.281%	1.496%	3.961%	4.705%	1.800%	1.721%	2.997%	16.768%	58.975%	100.197%	11.667%
	0.182	-0.723	-0.709	-0.519	-1.059	-0.304	-0.201	-0.292	-0.045	0.801	3.066	0.197	-2.363
	0.241	0.129	0.071	0.084	0.226	0.268	0.101	0.067	0.171	0.960	3.357	5.675	0.631
9	4.238%	2.271%	1.254%	1.488%	3.974%	4.714%	1.778%	1.171%	3.010%	16.900%	59.107%	99.906%	11.113%
	0.204	-0.728	-0.735	-0.528	-1.046	-0.295	-0.223	-0.842	-0.032	0.933	3.198	-0.094	-2.918
	0.230	0.166	0.107	0.111	0.279	0.259	0.103	0.082	0.127	0.919	3.275	5.659	0.728
10	4.058%	2.931%	1.879%	1.950%	4.920%	4.560%	1.809%	1.452%	2.245%	16.174%	57.655%	99.633%	12.812%
	0.023	-0.067	-0.110	-0.066	-0.100	-0.449	-0.192	-0.560	-0.798	0.207	1.746	-0.367	-1.219
	0.234	0.167	0.113	0.110	0.283	0.173	0.068	0.114	0.171	0.940	3.322	5.696	0.683
11	4.128%	2.949%	1.989%	1.932%	4.978%	3.050%	1.202%	2.003%	3.010%	16.548%	58.491%	100.280%	12.020%
	0.094	-0.050	0.0	-0.084	-0.043	-1.959	-0.800	-0.010	-0.032	0.581	2.582	0.280	-2.011
	0.238	0.168	0.114	0.110	0.283	0.174	0.069	0.110	0.164	0.948	3.322	5.702	0.682
12	4.185%	2.962%	2.016%	1.945%	4.991%	3.072%	1.219%	1.937%	2.878%	16.680%	58.491%	100.377%	12.015%
	0.151	-0.037	0.026	-0.070	-0.029	-1.937	-0.782	-0.076	-0.164	0.713	2.582	0.377	-2.016
	0.240	0.169	0.114	0.110	0.287	0.176	0.068	0.081	0.125	0.960	3.395	5.725	0.658
13	4.221%	2.966%	2.011%	1.937%	5.048%	3.103%	1.197%	1.430%	2.201%	16.900%	59.768%	100.782%	11.593%
	0.186	-0.032	0.022	-0.079	0.028	-1.906	-0.804	-0.582	-0.842	0.933	3.858	0.782	-2.438
	0.231	0.168	0.112	0.111	0.282	0.281	0.110	0.081	0.126	0.920	3.270	5.695	0.758
14	4.071%	2.958%	1.981%	1.959%	4.973%	4.956%	1.941%	1.435%	2.227%	16.196%	57.567%	100.263%	13.344%
	0.037	-0.041	-0.009	-0.057	-0.047	-0.053	-0.060	-0.578	-0.816	0.229	1.658	0.263	-0.687

Continued

TABLE A-4 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
15	0.235 4.141% 0.107	0.118 2.082% -0.917	0.085 1.496% -0.493	0.093 1.637% -0.378	0.243 4.274% -0.747	0.283 4.987% -0.022	0.107 1.888% -0.113	0.080 1.413% -0.600	0.125 2.196% -0.846	0.948 16.680% 0.713	3.385 59.592% 3.682	5.702 100.386% 0.386	0.691 12.169% -1.862
16	0.242 4.256% 0.222	0.117 2.055% -0.943	0.085 1.496% -0.493	0.089 1.562% -0.453	0.242 4.260% -0.760	0.176 3.103% -1.906	0.065 1.140% -0.861	0.079 1.391% -0.622	0.123 2.165% -0.877	0.977 17.209% 1.241	3.490 61.440% 5.531	5.685 100.078% 0.078	0.582 10.250% -3.781
17	0.230 4.049% 0.015	0.119 2.104% -0.895	0.086 1.514% -0.475	0.094 1.650% -0.365	0.240 4.225% -0.795	0.282 4.960% -0.048	0.109 1.919% -0.082	0.114 2.011% -0.001	0.170 2.997% -0.045	0.935 16.460% 0.493	3.305 58.183% 2.274	5.684 100.073% 0.073	0.722 12.711% -1.320
18	0.263 4.630% 0.596	0.0 0.0 % -2.999	0.0 0.0 % -1.989	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.314 5.528% 0.519	0.111 1.954% -0.047	0.121 2.130% 0.117	0.177 3.116% 0.073	1.031 18.155% 2.187	3.675 64.697% 8.788	5.692 100.210% 0.210	0.435 7.658% -6.373
19	0.245 4.318% 0.283	0.170 2.988% -0.010	0.109 1.928% -0.062	0.109 1.910% -0.106	0.288 5.075% 0.054	0.0 0.0 % -5.009	0.0 0.0 % -2.001	0.118 2.069% 0.056	0.175 3.076% 0.034	0.980 17.253% 1.285	3.467 61.044% 5.135	5.661 99.660% -0.340	0.515 9.071% -4.960
20	0.271 4.780% 0.745	0.182 3.204% 0.205	0.121 2.135% 0.145	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.0 0.0 % -5.009	0.0 0.0 % -2.001	0.123 2.161% 0.148	0.180 3.164% 0.122	1.073 18.881% 2.914	3.773 66.413% 10.504	5.722 100.738% 0.738	0.244 4.296% -9.735
21	0.255 4.498% 0.464	0.163 2.874% -0.125	0.107 1.888% -0.101	0.063 1.109% -0.907	0.173 3.041% -1.979	0.0 0.0 % -5.009	0.0 0.0 % -2.001	0.118 2.073% 0.060	0.175 3.090% 0.047	1.023 18.001% 2.033	3.597 63.333% 7.423	5.675 99.906% -0.094	0.398 7.002% -7.029
22	0.230 4.045% 0.010	0.164 2.892% -0.107	0.105 1.848% -0.141	0.100 1.769% -0.246	0.258 4.542% -0.478	0.261 4.595% -0.414	0.104 1.826% -0.175	0.113 1.998% -0.015	0.172 3.032% -0.010	0.919 16.174% 0.207	3.255 57.303% 1.394	5.682 100.025% 0.025	0.737 12.983% -1.047

Continued

TABLE A-4 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
23	0.255 4.485% 0.450	0.175 3.085% 0.087	0.118 2.073% 0.084	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.182 3.204% -1.804	0.066 1.162% -0.839	0.116 2.042% 0.029	0.174 3.059% 0.016	1.020 17.957% 1.989	3.600 63.377% 7.467	5.705 100.443% 0.443	0.416 7.319% -6.712
24	0.233 4.102% 0.067	0.160 2.817% -0.182	0.104 1.831% -0.158	0.065 1.144% -0.871	0.166 2.931% -2.089	0.285 5.026% 0.018	0.112 1.976% -0.025	0.113 1.989% -0.023	0.172 3.024% -0.019	0.946 16.658% 0.691	3.310 58.271% 2.362	5.667 99.770% -0.230	0.669 11.777% -2.253
25	0.248 4.375% 0.340	0.178 3.134% 0.135	0.074 1.312% -0.678	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.298 5.251% 0.242	0.113 1.989% -0.012	0.116 2.051% 0.038	0.173 3.050% 0.007	0.999 17.583% 1.615	3.505 61.704% 5.795	5.706 100.447% 0.447	0.489 8.613% -5.418
26	0.248 4.370% 0.336	0.178 3.129% 0.131	0.115 2.029% 0.040	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.298 5.251% 0.242	0.113 1.994% -0.007	0.118 2.077% 0.065	0.174 3.072% 0.029	0.992 17.473% 1.505	3.467 61.044% 5.135	5.705 100.439% 0.439	0.531 9.357% -4.674
27	0.246 4.326% 0.292	0.176 3.094% 0.095	0.112 1.972% -0.018	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.295 5.202% 0.194	0.113 1.981% -0.021	0.115 2.029% 0.016	0.172 3.028% -0.015	0.977 17.209% 1.241	3.457 60.868% 4.959	5.664 99.708% -0.292	0.523 9.203% -4.828
28	0.229 4.023% -0.012	0.169 2.971% -0.028	0.105 1.848% -0.141	0.110 1.937% -0.079	0.206 3.631% -1.389	0.283 4.991% -0.018	0.113 1.994% -0.007	0.113 1.989% -0.023	0.172 3.028% -0.015	0.923 16.240% 0.273	3.250 57.215% 1.306	5.673 99.867% -0.133	0.708 12.460% -1.571
29	0.227 3.992% -0.043	0.164 2.883% -0.116	0.106 1.870% -0.119	0.104 1.835% -0.180	0.219 3.851% -1.169	0.231 4.075% -0.933	0.109 1.923% -0.078	0.117 2.064% 0.051	0.166 2.918% -0.125	0.931 16.394% 0.427	3.330 58.623% 2.714	5.705 100.430% 0.430	0.674 11.861% -2.170
30	0.226 3.974% -0.060	0.163 2.865% -0.134	0.106 1.862% -0.128	0.104 1.840% -0.176	0.218 3.847% -1.174	0.231 4.071% -0.937	0.109 1.923% -0.078	0.109 1.910% -0.103	0.166 2.931% -0.111	0.931 16.394% 0.427	3.327 58.579% 2.670	5.691 100.197% 0.197	0.664 11.689% -2.341

Continued

TABLE A-4 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
31	0.218 3.842% -0.192	0.163 2.870% -0.129	0.106 1.870% -0.119	0.109 1.923% -0.092	0.284 5.000% -0.021	0.284 5.009% 0.000	0.112 1.976% -0.025	0.108 1.906% -0.107	0.166 2.918% -0.125	0.885 15.580% -0.387	3.207 56.467% 0.557	5.644 99.360% -0.640	0.783 13.784% -0.246
32	0.222 3.913% -0.122	0.164 2.887% -0.111	0.112 1.972% -0.018	0.109 1.928% -0.088	0.287 5.061% 0.041	0.229 4.040% -0.968	0.111 1.963% -0.038	0.109 1.919% -0.094	0.166 2.931% -0.111	0.915 16.108% 0.141	3.290 57.919% 2.010	5.717 100.641% 0.641	0.738 12.992% -1.039
33	0.220 3.864% -0.170	0.164 2.896% -0.103	0.113 1.994% 0.004	0.110 1.945% -0.070	0.287 5.053% 0.032	0.285 5.026% 0.018	0.114 2.011% 0.010	0.109 1.928% -0.085	0.169 2.975% -0.067	0.895 15.756% -0.211	3.225 56.775% 0.866	5.693 100.223% 0.223	0.795 14.000% -0.031
34	0.222 3.908% -0.126	0.163 2.870% -0.129	0.107 1.892% -0.097	0.108 1.906% -0.110	0.285 5.013% -0.007	0.229 4.023% -0.986	0.111 1.963% -0.038	0.108 1.906% -0.107	0.167 2.949% -0.094	0.910 16.020% 0.053	3.280 57.743% 1.834	5.691 100.192% 0.192	0.729 12.834% -1.197
35	0.219 3.860% -0.175	0.162 2.856% -0.142	0.107 1.879% -0.110	0.110 1.937% -0.079	0.282 4.973% -0.047	0.285 5.026% 0.018	0.112 1.967% -0.034	0.106 1.875% -0.138	0.169 2.984% -0.059	0.892 15.712% -0.255	3.225 56.775% 0.866	5.671 99.845% -0.155	0.781 13.754% -0.277
36	0.222 3.908% -0.126	0.161 2.843% -0.156	0.113 1.998% 0.009	0.104 1.831% -0.185	0.225 3.961% -1.059	0.226 3.974% -1.034	0.110 1.932% -0.069	0.107 1.888% -0.125	0.165 2.905% -0.138	0.921 16.218% 0.251	3.302 58.139% 2.230	5.657 99.598% -0.402	0.671 11.821% -2.209
37	0.221 3.891% -0.144	0.164 2.887% -0.111	0.115 2.025% 0.035	0.105 1.848% -0.167	0.227 4.001% -1.020	0.285 5.017% 0.009	0.110 1.941% -0.060	0.107 1.888% -0.125	0.166 2.922% -0.120	0.903 15.888% -0.079	3.275 57.655% 1.746	5.678 99.963% -0.037	0.734 12.931% -1.100
38	0.220 3.882% -0.153	0.164 2.896% -0.103	0.115 2.020% 0.031	0.105 1.857% -0.158	0.227 4.001% -1.020	0.285 5.017% 0.009	0.111 1.963% -0.038	0.108 1.897% -0.116	0.169 2.980% -0.063	0.906 15.954% -0.013	3.267 57.523% 1.614	5.680 99.990% -0.010	0.735 12.935% -1.096

Continued

TABLE A-4 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.221	0.162	0.106	0.109	0.284	0.227	0.110	0.108	0.166	0.906	3.262	5.664	0.726
39	3.886%	2.861%	1.875%	1.919%	5.004%	4.005%	1.945%	1.901%	2.931%	15.954%	57.435%	99.717%	12.785%
	-0.148	-0.138	-0.114	-0.097	-0.016	-1.003	-0.056	-0.111	-0.111	-0.013	1.526	-0.283	-1.246
	0.228	0.164	0.105	0.102	0.256	0.282	0.114	0.113	0.172	0.909	3.220	5.665	0.757
40	4.018%	2.887%	1.857%	1.791%	4.507%	4.969%	2.003%	1.994%	3.028%	15.998%	56.687%	99.739%	13.327%
	-0.016	-0.111	-0.132	-0.224	-0.513	-0.040	0.001	-0.019	-0.015	0.031	0.778	-0.261	-0.704
	0.227	0.167	0.105	0.113	0.278	0.257	0.104	0.113	0.171	0.907	3.200	5.643	0.754
41	4.001%	2.949%	1.857%	1.981%	4.894%	4.529%	1.822%	1.998%	3.010%	15.976%	56.335%	99.352%	13.278%
	-0.034	-0.050	-0.132	-0.035	-0.126	-0.480	-0.179	-0.015	-0.032	0.009	0.425	-0.648	-0.753
	0.267	0.0	0.0	0.0	0.0	0.288	0.104	0.123	0.179	1.050	3.693	5.704	0.411
42	4.709%	0.0 %	0.0 %	0.0 %	0.0 %	5.075%	1.835%	2.170%	3.147%	18.485%	65.005%	100.426%	7.244%
	0.675	-2.999	-1.989	-2.016	-5.020	0.066	-0.166	0.157	0.104	2.517	9.096	0.426	-6.787
	0.248	0.175	0.115	0.0	0.0	0.272	0.102	0.118	0.174	0.996	3.492	5.693	0.505
43	4.357%	3.090%	2.025%	0.0 %	0.0 %	4.797%	1.804%	2.073%	3.063%	17.539%	61.484%	100.232%	8.895%
	0.323	0.091	0.035	-2.016	-5.020	-0.211	-0.197	0.060	0.021	1.571	5.575	0.232	-5.136
	0.249	0.168	0.109	0.100	0.267	0.0	0.0	0.118	0.175	0.995	3.505	5.686	0.494
44	4.392%	2.962%	1.923%	1.752%	4.705%	0.0 %	0.0 %	2.073%	3.081%	17.517%	61.704%	100.109%	8.701%
	0.358	-0.037	-0.066	-0.264	-0.315	-5.009	-2.001	0.060	0.038	1.549	5.795	0.109	-5.330
	0.264	0.0	0.0	0.0	0.0	0.307	0.110	0.114	0.167	1.025	3.680	5.667	0.421
45	4.652%	0.0 %	0.0 %	0.0 %	0.0 %	5.409%	1.932%	2.003%	2.949%	18.045%	64.785%	99.774%	7.412%
	0.618	-2.999	-1.989	-2.016	-5.020	0.401	-0.069	-0.010	-0.094	2.077	8.876	-0.226	-6.619
	0.249	0.173	0.113	0.111	0.290	0.0	0.0	0.113	0.169	0.987	3.505	5.710	0.516
46	4.392%	3.046%	1.989%	1.954%	5.114%	0.0 %	0.0 %	1.981%	2.966%	17.385%	61.704%	100.531%	9.084%
	0.358	0.047	0.0	-0.062	0.094	-5.009	-2.001	-0.032	-0.076	1.417	5.795	0.531	-4.947

Continued

TABLE A-4 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.248	0.176	0.117	0.0	0.0	0.296	0.111	0.110	0.165	0.984	3.497	5.705	0.523
47	4.362%	3.098%	2.064%	0.0 %	0.0 %	5.207%	1.963%	1.945%	2.905%	17.319%	61.572%	100.434%	9.216%
	0.327	0.100	0.075	-2.016	-5.020	0.198	-0.038	-0.067	-0.138	1.351	5.663	0.434	-4.815
	0.234	0.174	0.097	0.116	0.289	0.287	0.115	0.064	0.175	0.921	3.202	5.675	0.738
48	4.119%	3.054%	1.708%	2.051%	5.088%	5.057%	2.020%	1.135%	3.076%	16.218%	56.379%	99.906%	12.988%
	0.085	0.056	-0.282	0.035	0.067	0.048	0.019	-0.877	0.034	0.251	0.469	-0.094	-1.043
	0.237	0.174	0.057	0.115	0.291	0.290	0.112	0.063	0.175	0.946	3.300	5.759	0.700
49	4.172%	3.054%	1.003%	2.025%	5.123%	5.105%	1.972%	1.100%	3.076%	16.658%	58.095%	101.385%	12.332%
	0.138	0.056	-0.986	0.009	0.103	0.097	-0.029	-0.913	0.034	0.691	2.186	1.385	-1.699
	0.235	0.174	0.056	0.115	0.286	0.286	0.113	0.112	0.174	0.927	3.240	5.719	0.740
50	4.137%	3.063%	0.986%	2.029%	5.039%	5.035%	1.998%	1.972%	3.054%	16.328%	57.039%	100.681%	13.032%
	0.103	0.065	-1.003	0.013	0.019	0.026	-0.003	-0.041	0.012	0.361	1.130	0.681	-0.999
	0.240	0.172	0.055	0.112	0.292	0.141	0.110	0.114	0.173	0.963	3.350	5.722	0.602
51	4.225%	3.032%	0.968%	1.972%	5.141%	2.473%	1.937%	2.016%	3.046%	16.944%	58.975%	100.729%	10.598%
	0.191	0.034	-1.021	-0.044	0.120	-2.535	-0.065	0.003	0.003	0.977	3.066	0.729	-3.433
	0.231	0.162	0.112	0.111	0.288	0.137	0.109	0.109	0.169	0.985	3.280	5.693	0.646
52	4.075%	2.848%	1.981%	1.954%	5.070%	2.407%	1.919%	1.919%	2.966%	17.341%	57.743%	100.223%	11.377%
	0.041	-0.151	-0.009	-0.062	0.050	-2.601	-0.082	-0.094	-0.076	1.373	1.834	0.223	-2.654
	0.233	0.164	0.113	0.109	0.288	0.137	0.107	0.061	0.167	0.949	3.317	5.645	0.599
53	4.097%	2.896%	1.981%	1.910%	5.070%	2.421%	1.884%	1.074%	2.949%	16.702%	58.403%	99.387%	10.545%
	0.063	-0.103	-0.009	-0.106	0.050	-2.588	-0.117	-0.939	-0.094	0.735	2.494	-0.613	-3.486
	0.234	0.167	0.114	0.105	0.135	0.289	0.109	0.065	0.171	0.954	3.327	5.672	0.603
54	4.128%	2.949%	2.011%	1.853%	2.385%	5.083%	1.919%	1.144%	3.006%	16.790%	58.579%	99.849%	10.624%
	0.094	-0.050	0.022	-0.163	-2.635	0.075	-0.082	-0.868	-0.037	0.823	2.670	-0.151	-3.406

Continued

TABLE A-4 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.233	0.169	0.114	0.108	0.139	0.288	0.111	0.112	0.171	0.948	3.300	5.694	0.654
55	4.102%	2.975%	2.016%	1.897%	2.451%	5.075%	1.963%	1.976%	3.010%	16.680%	58.095%	100.241%	11.518%
	0.067	-0.023	0.026	-0.119	-2.569	0.066	-0.038	-0.037	-0.032	0.713	2.186	0.241	-2.513
	0.234	0.169	0.072	0.107	0.129	0.288	0.111	0.113	0.171	0.949	3.327	5.672	0.603
56	4.124%	2.980%	1.268%	1.884%	2.275%	5.075%	1.963%	1.994%	3.015%	16.702%	58.579%	99.858%	10.611%
	0.089	-0.019	-0.722	-0.132	-2.745	0.066	-0.038	-0.019	-0.028	0.735	2.670	-0.142	-3.420
	0.241	0.168	0.115	0.109	0.293	0.0	0.111	0.062	0.169	0.987	3.405	5.662	0.470
57	4.252%	2.953%	2.020%	1.928%	5.167%	0.0 %	1.959%	1.091%	2.980%	17.385%	59.944%	99.677%	8.279%
	0.217	-0.045	0.031	-0.088	0.147	-5.009	-0.043	-0.921	-0.063	1.417	4.034	-0.323	-5.752
	0.239	0.168	0.108	0.109	0.287	0.0	0.113	0.118	0.173	0.976	3.412	5.704	0.512
58	4.212%	2.962%	1.901%	1.919%	5.053%	0.0 %	1.985%	2.069%	3.050%	17.186%	60.076%	100.412%	9.022%
	0.178	-0.037	-0.088	-0.097	0.032	-5.009	-0.016	0.056	0.007	1.219	4.166	0.412	-5.009
	0.240	0.174	0.110	0.122	0.0	0.292	0.112	0.116	0.173	0.975	3.407	5.722	0.519
59	4.234%	3.059%	1.941%	2.148%	0.0 %	5.149%	1.967%	2.047%	3.041%	17.164%	59.988%	100.738%	9.137%
	0.200	0.060	-0.048	0.132	-5.020	0.141	-0.034	0.034	-0.001	1.197	4.078	0.738	-4.894
	0.248	0.175	0.112	0.122	0.0	0.297	0.112	0.0	0.178	0.997	3.497	5.740	0.409
60	4.362%	3.085%	1.972%	2.152%	0.0 %	5.237%	1.972%	0.0 %	3.134%	17.561%	61.572%	101.046%	7.209%
	0.327	0.087	-0.018	0.136	-5.020	0.229	-0.029	-2.013	0.091	1.593	5.663	1.046	-6.822
	0.233	0.170	0.109	0.113	0.283	0.285	0.113	0.0	0.175	0.926	3.302	5.710	0.677
61	4.097%	2.993%	1.910%	1.985%	4.987%	5.017%	1.998%	0.0 %	3.090%	16.306%	58.139%	100.522%	11.914%
	0.063	-0.006	-0.079	-0.031	-0.034	0.009	-0.003	-2.013	0.047	0.339	2.230	0.522	-2.117
	0.233	0.168	0.0	0.113	0.281	0.287	0.114	0.117	0.175	0.925	3.275	5.688	0.685
62	4.102%	2.958%	0.0 %	1.994%	4.951%	5.048%	2.016%	2.055%	3.081%	16.284%	57.655%	100.144%	12.055%
	0.067	-0.041	-1.989	-0.022	-0.069	0.040	0.015	0.043	0.038	0.317	1.746	0.144	-1.976

Continued

TABLE A-4 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.241	0.0	0.0	0.106	0.276	0.293	0.113	0.118	0.174	0.957	3.400	5.679	0.687
63	4.243%	0.0 %	0.0 %	1.875%	4.859%	5.158%	1.998%	2.073%	3.059%	16.856%	59.856%	99.977%	12.090%
	0.208	-2.999	-1.989	-0.141	-0.161	0.150	-0.003	0.060	0.016	0.889	3.946	-0.023	-1.941
	0.232	0.143	0.050	0.107	0.271	0.285	0.114	0.114	0.174	0.925	3.262	5.677	0.720
64	4.080%	2.522%	0.876%	1.892%	4.780%	5.017%	2.003%	2.003%	3.054%	16.284%	57.435%	99.946%	12.675%
	0.045	-0.477	-1.113	-0.123	-0.241	0.009	0.001	-0.010	0.012	0.317	1.526	-0.054	-1.356
	0.228	0.167	0.089	0.110	0.274	0.283	0.114	0.114	0.174	0.909	3.215	5.679	0.761
65	4.018%	2.949%	1.576%	1.945%	4.828%	4.987%	2.011%	2.007%	3.054%	15.998%	56.599%	99.972%	13.397%
	-0.016	-0.050	-0.414	-0.070	-0.192	-0.022	0.010	-0.006	0.012	0.031	0.690	-0.028	-0.634
	0.244	0.174	0.111	0.114	0.291	0.294	0.115	0.0	0.0	0.960	3.403	5.706	0.696
66	4.300%	3.068%	1.950%	2.003%	5.123%	5.185%	2.020%	0.0 %	0.0 %	16.900%	59.900%	100.447%	12.257%
	0.266	0.069	-0.040	-0.013	0.103	0.176	0.019	-2.013	-3.043	0.933	3.990	0.447	-1.774
	0.228	0.168	0.109	0.113	0.278	0.283	0.114	0.108	0.164	0.901	3.197	5.664	0.778
67	4.018%	2.958%	1.928%	1.989%	4.890%	4.978%	2.007%	1.906%	2.878%	15.866%	56.291%	99.708%	13.701%
	-0.016	-0.041	-0.062	-0.026	-0.131	-0.031	0.006	-0.107	-0.164	-0.101	0.381	-0.292	-0.330

TABLE A-5 [1] .. FLOW DISTRIBUTION (AV REYNOLDS NO = 1300)

UNSTEADINESS PARAMETER: 21.768

PULSE RATE: 90.000

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
1	0.304 5.361% 1.326	0.213 3.756% 0.757	0.151 2.664% 0.675	0.139 2.456% 0.440	0.365 6.434% 1.414	0.367 6.458% 1.449	0.132 2.318% 0.317	0.140 2.468% 0.455	0.210 3.703% 0.660	1.288 22.675% 6.707	4.167 73.353% 17.443	7.478 131.644% 31.644	1.024 18.024% 3.993
2	0.305 5.369% 1.335	0.215 3.781% 0.782	0.152 2.676% 0.687	0.141 2.487% 0.471	0.367 6.461% 1.441	0.335 5.902% 0.893	0.119 2.095% 0.094	0.134 2.355% 0.342	0.201 3.534% 0.491	1.300 22.886% 6.919	4.202. 73.983% 18.074	7.471 131.528% 31.528	0.988 17.393% 3.362
3	0.304 5.356% 1.322	0.212 3.728% 0.729	0.128 2.262% 0.273	0.130 2.284% 0.268	0.344 6.056% 1.036	0.336 5.915% 0.907	0.118 2.069% 0.067	0.133 2.346% 0.333	0.201 3.534% 0.491	1.307 23.018% 7.051	4.212 74.159% 18.250	7.426 130.727% 30.727	0.942 16.579% 2.548
4	0.300 5.290% 1.256	0.206 3.618% 0.619	0.121 2.126% 0.136	0.131 2.302% 0.286	0.352 6.206% 1.185	0.368 6.474% 1.466	0.130 2.293% 0.292	0.140 2.473% 0.461	0.210 3.701% 0.659	1.295 22.798% 6.831	4.212 74.159% 18.250	7.466 131.440% 31.440	0.981 17.279% 3.248
5	0.340 5.990% 1.956	0.227 4.005% 1.006	0.134 2.359% 0.370	0.147 2.588% 0.572	0.386 6.800% 1.780	0.245 4.318% -0.691	0.080 1.404% -0.597	0.0 0.0 % -2.013	0.0 0.0 % -3.043	1.409 24.800% 8.833	4.500 79.221% 23.311	7.469 131.484% 31.484	0.765 13.476% -0.555
6	0.343 6.034% 2.000	0.185 3.266% 0.267	0.105 1.853% -0.136	0.117 2.060% 0.044	0.313 5.519% 0.499	0.371 6.527% 1.518	0.130 2.297% 0.296	0.0 0.0 % -2.013	0.0 0.0 % -3.043	1.404 24.712% 8.745	4.502 79.265% 23.355	7.471 131.533% 31.533	0.789 13.899% -0.132

Continued

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[1] 1st Row: Flow, litres/minute
2nd Row: % of the reference total flow as given in Table A-2
3rd Row: Deviation from normal flow (2nd row minus figures of Table A-2)
Description of Blockages for each case is given in Table A-1

TABLE A-5 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.370	0.0	0.0	0.0	0.0	0.393	0.137	0.113	0.176	1.502	4.770	7.463	0.506
7	6.518%	0.0 %	0.0 %	0.0 %	0.0 %	6.923%	2.412%	1.994%	3.107%	26.451%	83.974%	131.379%	8.917%
	2.484	-2.999	-1.989	-2.016	-5.020	1.915	0.411	-0.019	0.065	10.484	28.065	31.379	-5.114
	0.322	0.171	0.099	0.109	0.294	0.351	0.122	0.120	0.215	1.341	4.350	7.495	0.865
8	5.664%	3.015%	1.743%	1.915%	5.185%	6.184%	2.152%	2.117%	3.785%	23.612%	76.580%	131.951%	15.228%
	1.630	0.016	-0.246	-0.101	0.164	1.175	0.151	0.104	0.742	7.645	20.671	31.951	1.197
	0.320	0.172	0.099	0.109	0.295	0.350	0.122	0.076	0.215	1.349	4.320	7.428	0.820
9	5.633%	3.028%	1.743%	1.928%	5.198%	6.157%	2.148%	1.338%	3.789%	23.753%	76.052%	130.767%	14.436%
	1.599	0.029	-0.246	-0.088	0.178	1.149	0.147	-0.675	0.747	7.786	20.143	30.767	0.405
	0.301	0.203	0.153	0.133	0.357	0.330	0.114	0.091	0.144	1.305	4.247	7.379	0.931
10	5.299%	3.569%	2.698%	2.346%	6.285%	5.805%	2.011%	1.606%	2.544%	22.974%	74.776%	129.913%	16.394%
	1.265	0.571	0.709	0.330	1.265	0.797	0.010	-0.406	-0.499	7.007	18.866	29.913	2.363
	0.302	0.206	0.160	0.132	0.356	0.216	0.070	0.136	0.206	1.315	4.297	7.398	0.868
11	5.325%	3.627%	2.817%	2.324%	6.267%	3.811%	1.237%	2.394%	3.627%	23.150%	75.656%	130.234%	15.290%
	1.291	0.628	0.827	0.308	1.247	-1.197	-0.764	0.381	0.584	7.183	19.746	30.234	1.259
	0.311	0.212	0.163	0.137	0.366	0.224	0.072	0.132	0.201	1.345	4.332	7.495	0.884
12	5.484%	3.732%	2.874%	2.412%	6.439%	3.935%	1.276%	2.324%	3.530%	23.678%	76.272%	131.955%	15.571%
	1.449	0.734	0.885	0.396	1.419	-1.074	-0.725	0.311	0.487	7.711	20.363	31.955	1.540
	0.315	0.211	0.161	0.136	0.365	0.223	0.072	0.096	0.148	1.342	4.377	7.449	0.846
13	5.541%	3.723%	2.843%	2.399%	6.426%	3.935%	1.268%	1.686%	2.614%	23.634%	77.064%	131.132%	14.889%
	1.507	0.725	0.854	0.383	1.405	-1.074	-0.734	-0.327	-0.428	7.667	21.155	31.132	0.858
	0.302	0.206	0.156	0.132	0.357	0.358	0.124	0.092	0.145	1.309	4.282	7.463	0.963
14	5.321%	3.622%	2.746%	2.328%	6.280%	6.302%	2.187%	1.620%	2.553%	23.040%	75.392%	131.392%	16.949%
	1.287	0.623	0.757	0.312	1.260	1.294	0.186	-0.393	-0.490	7.073	19.482	31.392	2.918

Continued

TABLE A-5 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.310	0.152	0.128	0.110	0.306	0.364	0.125	0.094	0.147	1.345	4.400	7.480	0.892
15	5.457%	2.672%	2.258%	1.932%	5.383%	6.404%	2.196%	1.655%	2.592%	23.678%	77.460%	131.687%	15.699%
	1.423	-0.327	0.268	-0.084	0.362	1.395	0.195	-0.358	-0.450	7.711	21.551	31.687	1.668
	0.326	0.161	0.134	0.116	0.317	0.236	0.075	0.098	0.155	1.387	4.482	7.488	0.785
16	5.735%	2.834%	2.355%	2.042%	5.589%	4.155%	1.320%	1.725%	2.729%	24.426%	78.913%	131.823%	13.824%
	1.700	-0.164	0.365	0.026	0.569	-0.854	-0.681	-0.288	-0.314	8.459	23.003	31.823	-0.207
	0.324	0.150	0.127	0.109	0.298	0.360	0.126	0.136	0.203	1.310	4.275	7.420	0.922
17	5.708%	2.636%	2.236%	1.923%	5.255%	6.342%	2.223%	2.399%	3.578%	23.062%	75.260%	130.622%	16.231%
	1.674	-0.362	0.246	-0.092	0.235	1.334	0.222	0.386	0.535	7.095	19.350	30.622	2.201
	0.351	0.0	0.0	0.0	0.0	0.406	0.142	0.153	0.231	1.457	4.680	7.423	0.560
18	6.184%	0.0 %	0.0 %	0.0 %	0.0 %	7.156%	2.509%	2.702%	4.075%	25.659%	82.390%	130.675%	9.859%
	2.149	-2.999	-1.989	-2.016	-5.020	2.148	0.508	0.690	1.033	9.691	26.480	30.675	-4.172
	0.324	0.218	0.160	0.140	0.376	0.0	0.0	0.144	0.217	1.382	4.452	7.415	0.681
19	5.699%	3.842%	2.821%	2.465%	6.628%	0.0 %	0.0 %	2.539%	3.816%	24.338%	78.385%	130.534%	11.989%
	1.665	0.844	0.832	0.449	1.608	-5.009	-2.001	0.527	0.773	8.371	22.475	30.534	-2.042
	0.366	0.251	0.184	0.0	0.0	0.0	0.0	0.161	0.243	1.520	4.757	7.483	0.345
20	6.443%	4.423%	3.239%	0.0 %	0.0 %	0.0 %	0.0 %	2.834%	4.282%	26.759%	83.754%	131.735%	6.074%
	2.409	1.425	1.250	-2.016	-5.020	-5.009	-2.001	0.822	1.240	10.792	27.845	31.735	-7.957
	0.339	0.217	0.163	0.078	0.229	0.0	0.0	0.147	0.226	1.440	4.585	7.425	0.540
21	5.968%	3.829%	2.870%	1.369%	4.040%	0.0 %	0.0 %	2.597%	3.979%	25.351%	80.717%	130.719%	9.506%
	1.934	0.830	0.880	-0.647	-0.980	-5.009	-2.001	0.584	0.936	9.383	24.808	30.719	-4.524
	0.297	0.198	0.150	0.115	0.319	0.327	0.114	0.132	0.201	1.295	4.232	7.382	0.929
22	5.229%	3.481%	2.641%	2.033%	5.625%	5.766%	2.007%	2.319%	3.547%	22.798%	74.512%	129.957%	16.350%
	1.194	0.483	0.651	0.018	0.604	0.757	0.006	0.307	0.505	6.831	18.602	29.957	2.319

Continued

TABLE A-5 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.338	0.227	0.172	0.0	0.0	0.241	0.076	0.146	0.222	1.432	4.595	7.450	0.559
23	5.950%	4.001%	3.024%	0.0 %	0.0 %	4.243%	1.342%	2.570%	3.908%	25.219%	80.893%	131.150%	9.837%
	1.916	1.002	1.034	-2.016	-5.020	-0.766	-0.659	0.557	0.866	9.251	24.984	31.150	-4.194
	0.303	0.196	0.150	0.069	0.207	0.364	0.127	0.135	0.206	1.322	4.280	7.360	0.856
24	5.330%	3.455%	2.641%	1.224%	3.644%	6.408%	2.240%	2.381%	3.627%	23.282%	75.348%	129.579%	15.074%
	1.295	0.456	0.651	-0.792	-1.376	1.400	0.239	0.368	0.584	7.315	19.438	29.579	1.043
	0.326	0.270	0.108	0.0	0.0	0.383	0.133	0.141	0.216	1.142	4.472	7.192	0.632
25	5.739%	4.753%	1.901%	0.0 %	0.0 %	6.747%	2.337%	2.487%	3.798%	20.113%	78.737%	126.612%	11.135%
	1.705	1.755	-0.088	-2.016	-5.020	1.738	0.336	0.474	0.756	4.146	22.827	26.612	-2.896
	0.324	0.222	0.165	0.0	0.0	0.381	0.133	0.143	0.215	1.385	4.445	7.414	0.689
26	5.699%	3.904%	2.914%	0.0 %	0.0 %	6.707%	2.350%	2.517%	3.789%	24.382%	78.253%	130.516%	12.138%
	1.665	0.905	0.924	-2.016	-5.020	1.699	0.349	0.505	0.747	8.415	22.343	30.516	-1.892
	0.326	0.224	0.162	0.0	0.0	0.387	0.136	0.142	0.217	1.385	4.442	7.422	0.691
27	5.748%	3.948%	2.856%	0.0 %	0.0 %	6.809%	2.399%	2.500%	3.820%	24.382%	78.208%	130.670%	12.165%
	1.714	0.949	0.867	-2.016	-5.020	1.800	0.398	0.487	0.778	8.415	22.299	30.670	-1.866
	0.296	0.204	0.150	0.128	0.253	0.359	0.126	0.132	0.201	1.307	4.240	7.396	0.893
28	5.220%	3.587%	2.641%	2.249%	4.450%	6.316%	2.218%	2.319%	3.539%	23.018%	74.644%	130.199%	15.725%
	1.185	0.588	0.651	0.233	-0.571	1.307	0.217	0.307	0.496	7.051	18.734	30.199	1.694
	0.287	0.191	0.147	0.114	0.276	0.289	0.114	0.149	0.189	1.297	4.342	7.398	0.862
29	5.061%	3.367%	2.592%	2.016%	4.859%	5.088%	2.016%	2.632%	3.323%	22.842%	76.448%	130.243%	15.171%
	1.027	0.368	0.603	0.0	-0.161	0.079	0.015	0.619	0.280	6.875	20.539	30.243	1.140
	0.288	0.190	0.147	0.115	0.277	0.289	0.114	0.140	0.189	1.301	4.355	7.406	0.852
30	5.066%	3.354%	2.592%	2.033%	4.872%	5.083%	2.011%	2.460%	3.332%	22.908%	76.668%	130.380%	15.008%
	1.031	0.355	0.603	0.018	-0.148	0.075	0.010	0.447	0.289	6.941	20.759	30.380	0.977

Continued

TABLE A-5 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.274	0.183	0.144	0.114	0.360	0.360	0.114	0.135	0.183	1.261	4.245	7.373	0.999
31	4.828%	3.217%	2.539%	2.011%	6.346%	6.333%	2.007%	2.372%	3.213%	22.204%	74.732%	129.803%	17.591%
	0.794	0.219	0.550	-0.004	1.326	1.325	0.006	0.359	0.170	6.236	18.822	29.803	3.561
	0.277	0.185	0.154	0.117	0.363	0.279	0.113	0.136	0.186	1.278	4.292	7.381	0.932
32	4.885%	3.257%	2.716%	2.060%	6.399%	4.912%	1.985%	2.390%	3.279%	22.490%	75.568%	129.940%	16.416%
	0.851	0.258	0.726	0.044	1.379	-0.097	-0.016	0.377	0.236	6.523	19.659	29.940	2.385
	0.273	0.183	0.153	0.114	0.359	0.359	0.113	0.135	0.183	1.256	4.246	7.373	1.006
33	4.802%	3.213%	2.698%	2.003%	6.324%	6.311%	1.989%	2.377%	3.217%	22.116%	74.754%	129.803%	17.710%
	0.767	0.214	0.709	-0.013	1.304	1.303	-0.012	0.364	0.175	6.148	18.844	29.803	3.679
	0.278	0.187	0.146	0.117	0.365	0.279	0.113	0.135	0.187	1.282	4.307	7.398	0.925
34	4.894%	3.292%	2.570%	2.060%	6.421%	4.916%	1.998%	2.377%	3.296%	22.578%	75.832%	130.234%	16.284%
	0.860	0.293	0.581	0.044	1.401	-0.092	-0.003	0.364	0.254	6.611	19.923	30.234	2.253
	0.273	0.182	0.145	0.116	0.355	0.359	0.113	0.131	0.186	1.262	4.257	7.380	0.989
35	4.810%	3.208%	2.553%	2.038%	6.254%	6.311%	1.989%	2.302%	3.274%	22.226%	74.952%	129.918%	17.420%
	0.776	0.210	0.563	0.022	1.234	1.303	-0.012	0.289	0.232	6.258	19.042	29.918	3.389
	0.283	0.188	0.157	0.113	0.283	0.283	0.114	0.136	0.189	1.299	4.352	7.397	0.859
36	4.978%	3.318%	2.764%	1.985%	4.978%	4.982%	2.003%	2.399%	3.323%	22.864%	76.624%	130.217%	15.122%
	0.943	0.320	0.775	-0.031	-0.043	-0.026	0.001	0.386	0.280	6.897	20.715	30.217	1.091
	0.277	0.186	0.156	0.112	0.279	0.361	0.113	0.135	0.185	1.280	4.302	7.387	0.931
37	4.885%	3.283%	2.746%	1.967%	4.912%	6.355%	1.998%	2.372%	3.257%	22.534%	75.744%	130.054%	16.385%
	0.851	0.285	0.757	-0.048	-0.109	1.347	-0.003	0.359	0.214	6.567	19.835	30.054	2.355
	0.278	0.186	0.155	0.111	0.279	0.361	0.113	0.135	0.188	1.280	4.300	7.387	0.931
38	4.890%	3.283%	2.738%	1.959%	4.912%	6.364%	1.998%	2.372%	3.305%	22.534%	75.700%	130.054%	16.385%
	0.855	0.285	0.748	-0.057	-0.109	1.356	-0.003	0.359	0.263	6.567	19.791	30.054	2.355

Continued

TABLE A-5 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
39	0.278 4.894% 0.860	0.187 3.288% 0.289	0.144 2.544% 0.555	0.116 2.051% 0.035	0.363 6.399% 1.379	0.280 4.920% -0.088	0.113 1.985% -0.016	0.136 2.390% 0.377	0.188 3.301% 0.258	1.280 22.534% 6.567	4.305 75.788% 19.879	7.390 130.094% 30.094	0.923 16.253% 2.223
40	0.296 5.215% 1.181	0.197 3.459% 0.461	0.150 2.641% 0.651	0.115 2.033% 0.018	0.317 5.585% 0.565	0.356 6.267% 1.259	0.125 2.201% 0.200	0.132 2.315% 0.302	0.201 3.534% 0.491	1.287 22.666% 6.699	4.202 73.983% 18.074	7.379 129.900% 29.900	0.955 16.808% 2.777
41	0.292 5.141% 1.106	0.199 3.499% 0.500	0.150 2.641% 0.651	0.128 2.258% 0.242	0.348 6.122% 1.102	0.322 5.664% 0.656	0.111 1.963% -0.038	0.132 2.319% 0.307	0.199 3.499% 0.456	1.290 22.710% 6.743	4.195 73.851% 17.942	7.365 129.667% 29.667	0.951 16.746% 2.716
42	0.359 6.320% 2.286	0.0 0.0 % -2.999	0.0 0.0 % -1.989	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.385 6.787% 1.778	0.135 2.372% 0.371	0.157 2.760% 0.747	0.237 4.172% 1.130	1.483 26.099% 10.131	4.675 82.302% 26.392	7.430 130.811% 30.811	0.542 9.546% -4.485
43	0.325 5.726% 1.692	0.222 3.908% 0.910	0.166 2.927% 0.937	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.353 6.210% 1.202	0.121 2.139% 0.138	0.143 2.522% 0.509	0.216 3.811% 0.769	1.392 24.514% 8.547	4.467 78.649% 22.739	7.407 130.406% 30.406	0.662 11.659% -2.372
44	0.329 5.796% 1.762	0.215 3.794% 0.795	0.161 2.834% 0.845	0.126 2.214% 0.198	0.346 6.091% 1.071	0.0 0.0 % -5.009	0.0 0.0 % -2.001	0.144 2.539% 0.527	0.219 3.855% 0.813	1.398 24.602% 8.635	4.467 78.649% 22.739	7.406 130.375% 30.375	0.651 11.465% -2.566
45	0.351 6.188% 2.154	0.0 0.0 % -2.999	0.0 0.0 % -1.989	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.406 7.147% 2.139	0.143 2.513% 0.512	0.144 2.544% 0.531	0.218 3.838% 0.795	1.455 25.615% 9.647	4.680 82.390% 26.480	7.398 130.234% 30.234	0.550 9.691% -4.340
46	0.324 5.708% 1.674	0.215 3.781% 0.782	0.163 2.874% 0.885	0.136 2.394% 0.378	0.370 6.514% 1.493	0.0 0.0 % -5.009	0.0 0.0 % -2.001	0.134 2.359% 0.346	0.204 3.596% 0.553	1.382 24.338% 8.371	4.487 79.001% 23.091	7.416 130.565% 30.565	0.667 11.747% -2.284

Continued

TABLE A-5 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
47	0.322 5.677% 1.643	0.219 3.860% 0.861	0.168 2.953% 0.964	0.0 0.0 % -2.016	0.0 0.0 % -5.020	0.380 6.694% 1.686	0.132 2.324% 0.323	0.133 2.341% 0.329	0.203 3.574% 0.531	1.372 24.162% 8.195	4.450 78.340% 22.431	7.380 129.926% 29.926	0.681 11.989% -2.042
48	0.307 5.413% 1.379	0.216 3.803% 0.804	0.126 2.214% 0.224	0.142 2.495% 0.480	0.368 6.483% 1.463	0.369 6.496% 1.488	0.133 2.350% 0.349	0.073 1.294% -0.719	0.212 3.732% 0.690	1.310 23.062% 7.095	4.210 74.115% 18.206	7.467 131.458% 31.458	0.936 16.487% 2.456
49	0.313 5.510% 1.476	0.219 3.855% 0.857	0.070 1.228% -0.761	0.142 2.500% 0.484	0.371 6.531% 1.511	0.372 6.558% 1.549	0.133 2.341% 0.340	0.074 1.303% -0.710	0.213 3.745% 0.703	1.302 22.930% 6.963	4.275 75.260% 19.350	7.484 131.762% 31.762	0.887 15.620% 1.589
50	0.307 5.409% 1.375	0.215 3.785% 0.786	0.067 1.180% -0.810	0.140 2.465% 0.449	0.367 6.456% 1.436	0.369 6.492% 1.483	0.131 2.306% 0.305	0.137 2.412% 0.399	0.210 3.697% 0.654	1.302 22.930% 6.963	4.210 74.115% 18.206	7.455 131.247% 31.247	0.939 16.540% 2.509
51	0.315 5.545% 1.511	0.221 3.891% 0.892	0.069 1.210% -0.779	0.144 2.544% 0.528	0.375 6.602% 1.581	0.172 3.037% -1.972	0.132 2.333% 0.332	0.140 2.465% 0.452	0.215 3.785% 0.742	1.349 23.744% 7.777	4.300 75.700% 19.791	7.433 130.855% 30.855	0.756 13.313% -0.717
52	0.300 5.277% 1.243	0.201 3.539% 0.540	0.161 2.830% 0.841	0.136 2.390% 0.374	0.363 6.386% 1.366	0.163 2.874% -2.135	0.124 2.179% 0.178	0.132 2.315% 0.302	0.203 3.569% 0.527	1.322 23.282% 7.315	4.250 74.820% 18.910	7.354 129.460% 29.460	0.818 14.405% 0.374
53	0.303 5.334% 1.300	0.207 3.653% 0.654	0.161 2.843% 0.854	0.137 2.403% 0.387	0.366 6.443% 1.423	0.166 2.918% -2.091	0.125 2.205% 0.204	0.070 1.232% -0.780	0.202 3.556% 0.513	1.340 23.590% 7.623	4.285 75.436% 19.526	7.362 129.614% 29.614	0.763 13.437% -0.594
54	0.305 5.365% 1.331	0.211 3.715% 0.716	0.164 2.896% 0.907	0.130 2.297% 0.282	0.165 2.900% -2.120	0.369 6.500% 1.492	0.130 2.289% 0.288	0.073 1.290% -0.723	0.207 3.644% 0.601	1.340 23.590% 7.623	4.295 75.612% 19.702	7.390 130.098% 30.098	0.772 13.586% -0.445

Continued

TABLE A-5 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
55	0.301 5.303% 1.269	0.211 3.706% 0.707	0.162 2.861% 0.871	0.130 2.297% 0.282	0.170 2.997% -2.023	0.365 6.421% 1.413	0.129 2.280% 0.279	0.136 2.394% 0.381	0.206 3.622% 0.579	1.327 23.370% 7.403	4.285 75.436% 19.526	7.423 130.688% 30.688	0.833 14.673% 0.643
56	0.307 5.405% 1.370	0.211 3.723% 0.725	0.105 1.857% -0.132	0.131 2.306% 0.290	0.158 2.786% -2.234	0.368 6.487% 1.479	0.130 2.289% 0.288	0.136 2.394% 0.381	0.208 3.657% 0.615	1.342 23.634% 7.667	4.310 75.876% 19.967	7.408 130.415% 30.415	0.768 13.525% -0.506
57	0.316 5.563% 1.529	0.214 3.776% 0.778	0.166 2.922% 0.933	0.141 2.482% 0.467	0.377 6.633% 1.612	0.0 0.0 % -5.009	0.129 2.267% 0.266	0.071 1.254% -0.758	0.210 3.697% 0.654	1.385 24.382% 8.415	4.397 77.416% 21.507	7.407 130.393% 30.393	0.614 10.809% -3.222
58	0.313 5.519% 1.485	0.211 3.710% 0.712	0.156 2.742% 0.753	0.136 2.390% 0.374	0.366 6.443% 1.423	0.0 0.0 % -5.009	0.126 2.214% 0.213	0.141 2.487% 0.474	0.211 3.710% 0.668	1.370 24.118% 8.151	4.405 77.548% 21.639	7.434 130.881% 30.881	0.663 11.672% -2.359
59	0.316 5.567% 1.533	0.218 3.833% 0.835	0.161 2.830% 0.841	0.146 2.575% 0.559	0.0 0.0 % -5.020	0.376 6.619% 1.611	0.132 2.319% 0.318	0.141 2.491% 0.478	0.213 3.750% 0.707	1.360 23.942% 7.975	4.362 76.800% 20.891	7.426 130.727% 30.727	0.678 11.940% -2.091
60	0.326 5.744% 1.709	0.222 3.913% 0.914	0.164 2.892% 0.902	0.147 2.597% 0.581	0.0 0.0 % -5.020	0.381 6.707% 1.699	0.135 2.381% 0.380	0.0 0.0 % -2.013	0.219 3.851% 0.808	1.387 24.426% 8.459	4.470 78.693% 22.783	7.453 131.203% 31.203	0.545 9.599% -4.432
61	0.303 5.339% 1.304	0.204 3.596% 0.597	0.152 2.685% 0.695	0.132 2.315% 0.299	0.356 6.272% 1.251	0.360 6.333% 1.325	0.126 2.223% 0.222	0.0 0.0 % -2.013	0.206 3.622% 0.579	1.305 22.974% 7.007	4.275 75.260% 19.350	7.419 130.617% 30.617	0.868 15.290% 1.259
62	0.299 5.268% 1.234	0.197 3.477% 0.478	0.0 0.0 % -1.989	0.130 2.289% 0.273	0.350 6.170% 1.150	0.358 6.298% 1.290	0.126 2.218% 0.217	0.136 2.385% 0.373	0.203 3.578% 0.535	1.300 22.886% 6.919	4.262 75.040% 19.130	7.362 129.609% 29.609	0.844 14.854% 0.823

Continued

TABLE A-5 .. Continued

CASE NO	CORO	RSCL	RVER	REXC	RINC	LINC	LEXC	LVER	LSCL	ILIA	RENS	TFLO	TFBR
	0.318	0.0	0.0	0.130	0.356	0.377	0.131	0.141	0.212	1.352	4.400	7.417	0.874
63	5.598%	0.0 %	0.0 %	2.293%	6.263%	6.633%	2.302%	2.487%	3.732%	23.810%	77.460%	130.578%	15.382%
	1.564	-2.999	-1.989	0.277	1.243	1.624	0.301	0.474	0.690	7.843	21.551	30.578	1.351
	0.301	0.165	0.081	0.124	0.341	0.357	0.126	0.133	0.202	1.310	4.255	7.397	0.913
64	5.299%	2.905%	1.426%	2.192%	6.008%	6.294%	2.223%	2.346%	3.565%	23.062%	74.908%	130.226%	16.073%
	1.265	-0.094	-0.563	0.176	0.987	1.285	0.222	0.333	0.522	7.095	18.998	30.226	2.042
	0.296	0.197	0.130	0.126	0.341	0.355	0.125	0.131	0.201	1.290	4.200	7.392	0.957
65	5.211%	3.459%	2.284%	2.218%	6.012%	6.245%	2.209%	2.311%	3.539%	22.710%	73.939%	130.138%	16.852%
	1.177	0.461	0.295	0.202	0.992	1.237	0.208	0.298	0.496	6.743	18.030	30.138	2.821
	0.318	0.213	0.157	0.136	0.367	0.372	0.130	0.0	0.0	1.355	4.427	7.476	0.897
66	5.598%	3.745%	2.773%	2.390%	6.470%	6.558%	2.284%	0.0 %	0.0 %	23.854%	77.944%	131.616%	15.800%
	1.564	0.747	0.783	0.374	1.449	1.549	0.283	-2.013	-3.043	7.887	22.035	31.616	1.769
	0.291	0.197	0.151	0.126	0.343	0.352	0.123	0.123	0.182	1.275	4.197	7.361	0.969
67	5.123%	3.473%	2.663%	2.227%	6.047%	6.192%	2.165%	2.165%	3.200%	22.446%	73.895%	129.596%	17.068%
	1.089	0.474	0.673	0.211	1.027	1.184	0.164	0.153	0.157	6.478	17.986	29.596	3.037

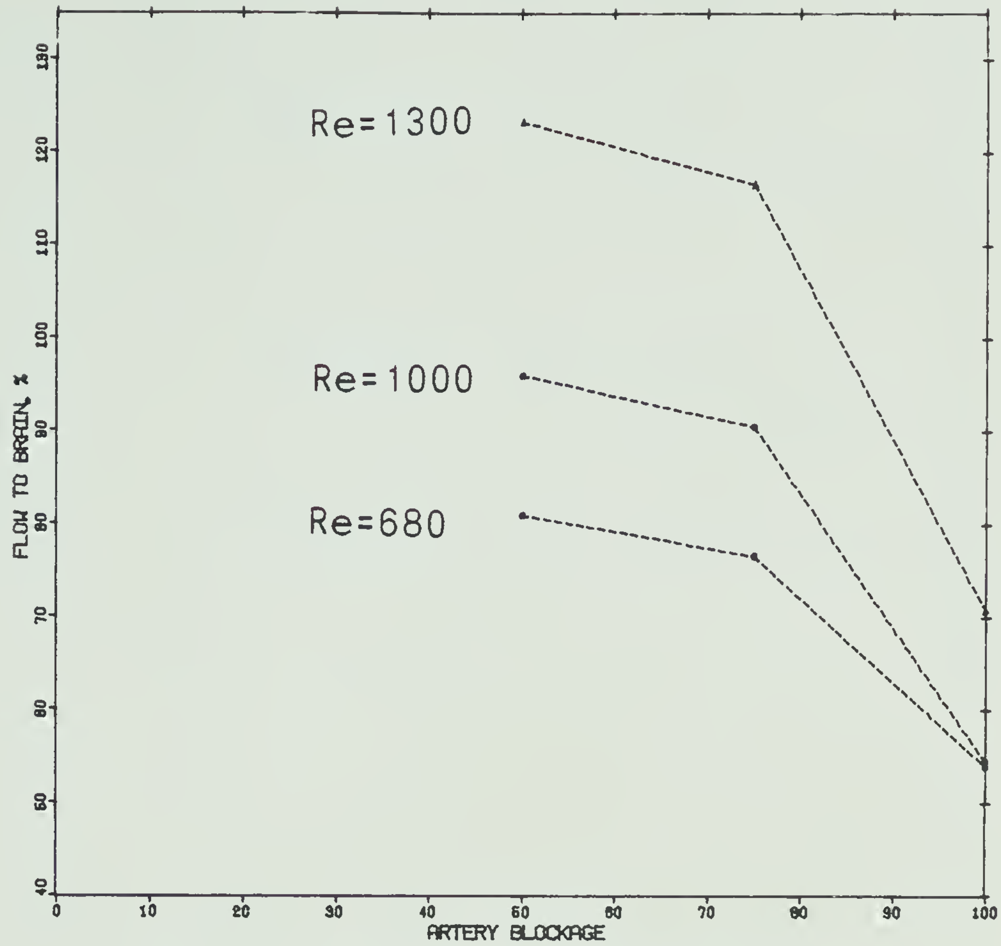

Fig A-1 .. BRACHIOCEPHALIC INVOLVED ONLY

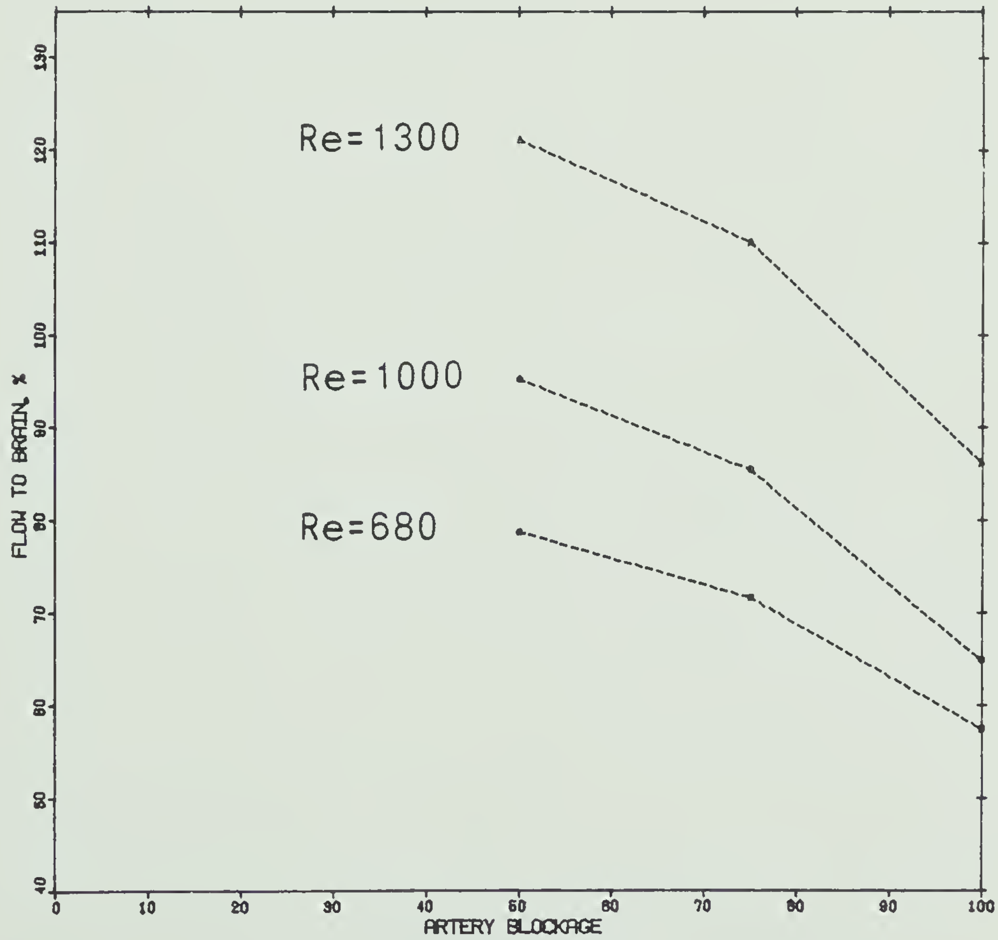

Fig A-2 .. LEFT COMMON CAROTID INVOLVED ONLY

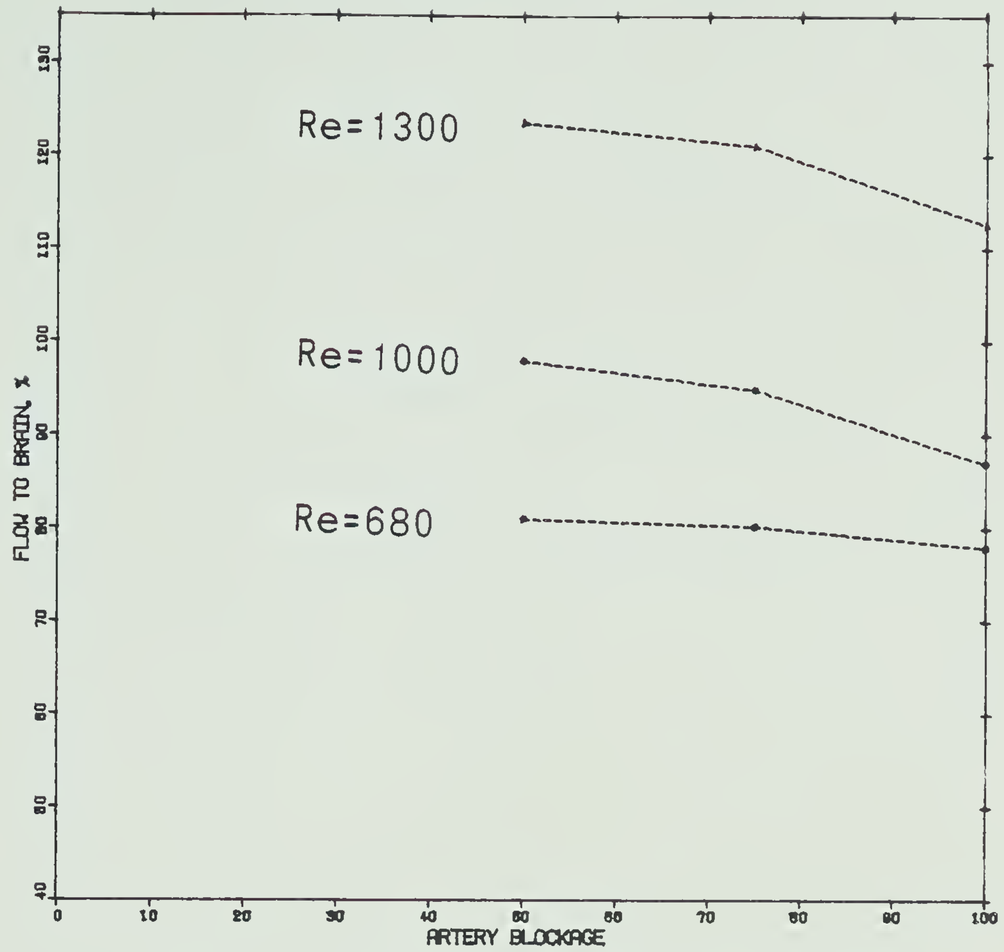

Fig A–3 .. LEFT SUBCLAVIAN INVOLVED ONLY

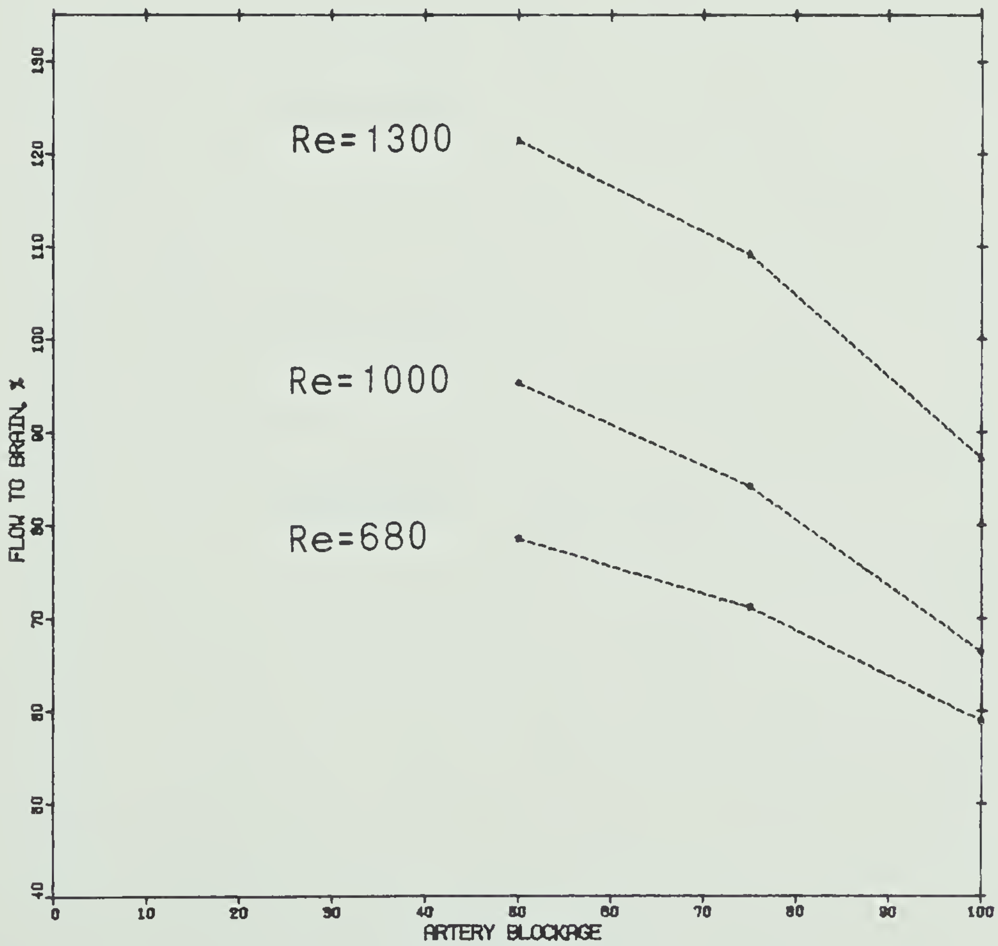

Fig A–4 .. RIGHT COMMON CAROTID INVOLVED ONLY

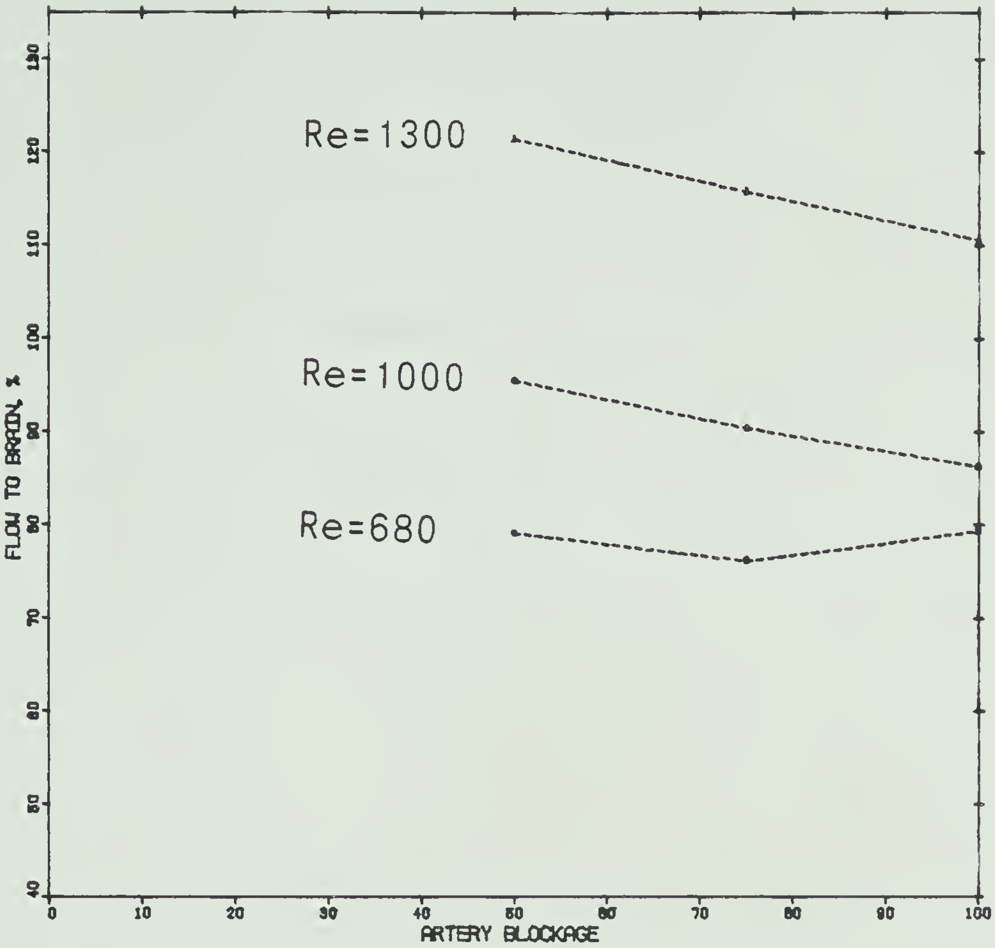

Fig A-5 .. RIGHT SUBCLAVIAN INVOLVED ONLY

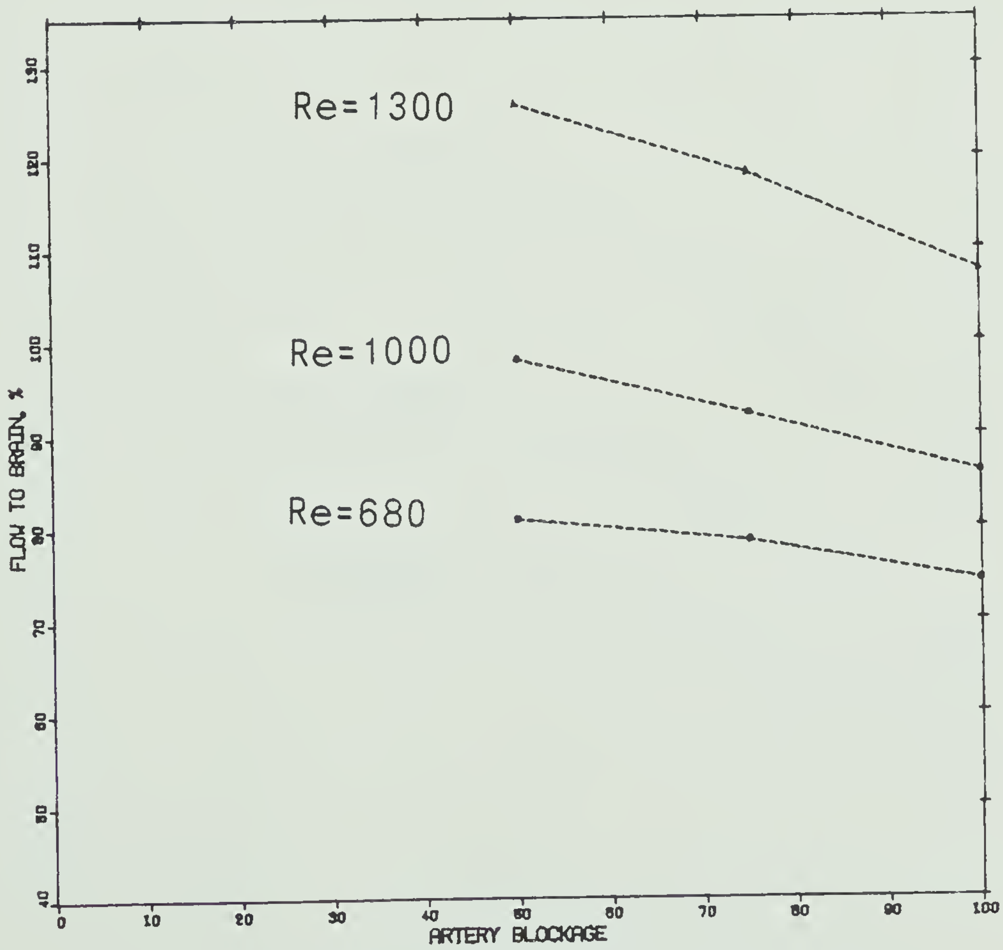

Fig A-6 .. RIGHT VERTEBRAL INVOLVED ONLY

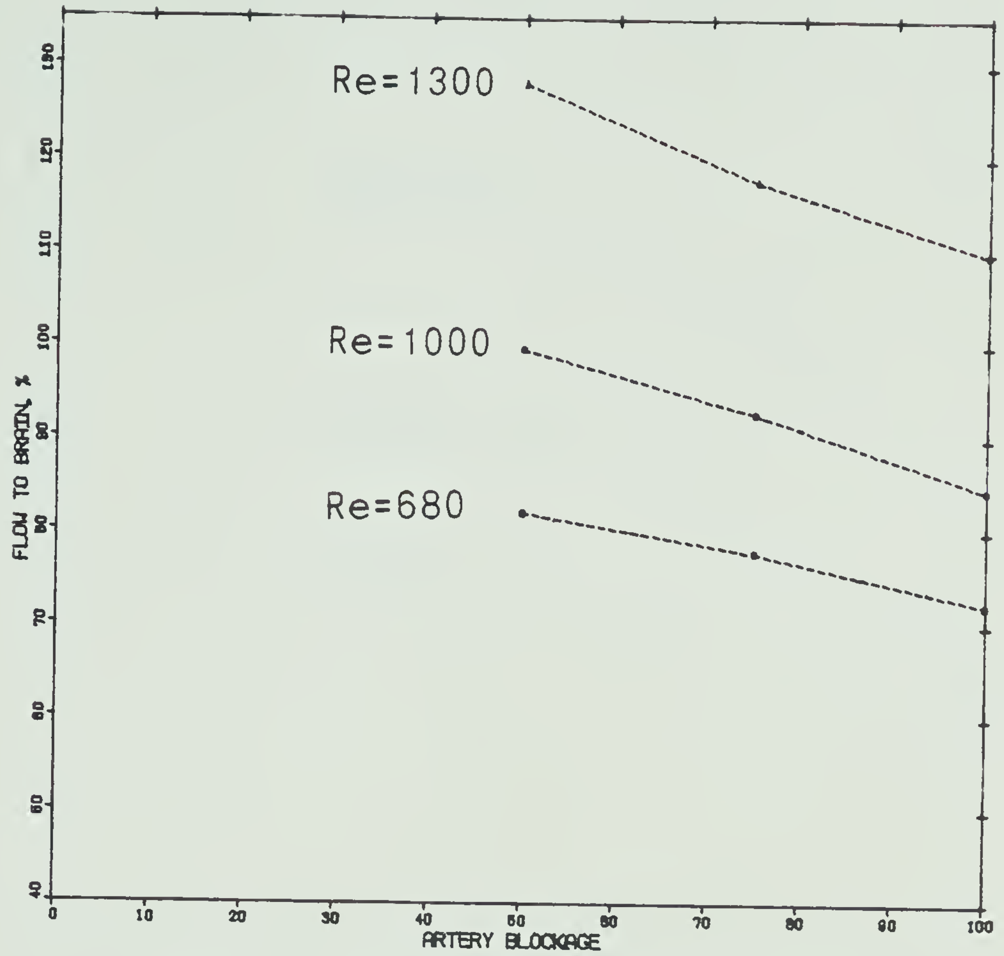

Fig A-7 .. LEFT VERTEBRAL INVOLVED ONLY

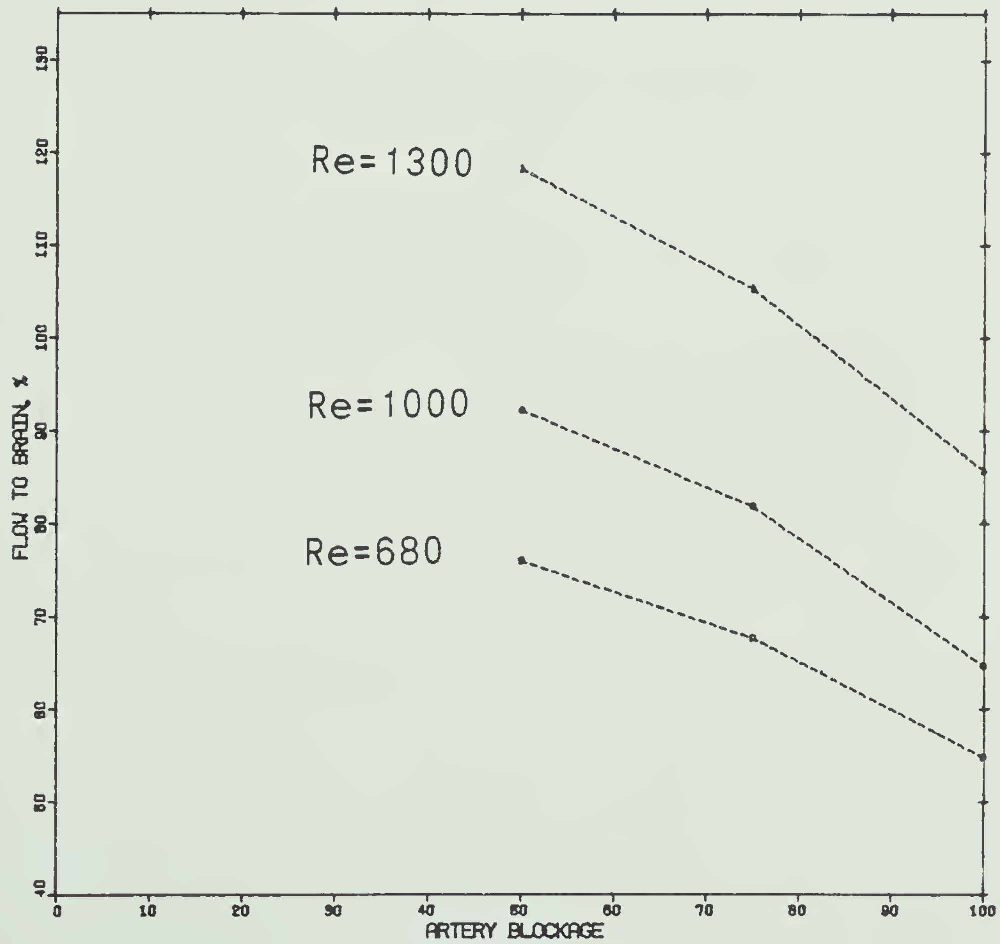

Fig A-8 .. RIGHT INTERNAL CAROTID INVOLVED ONLY

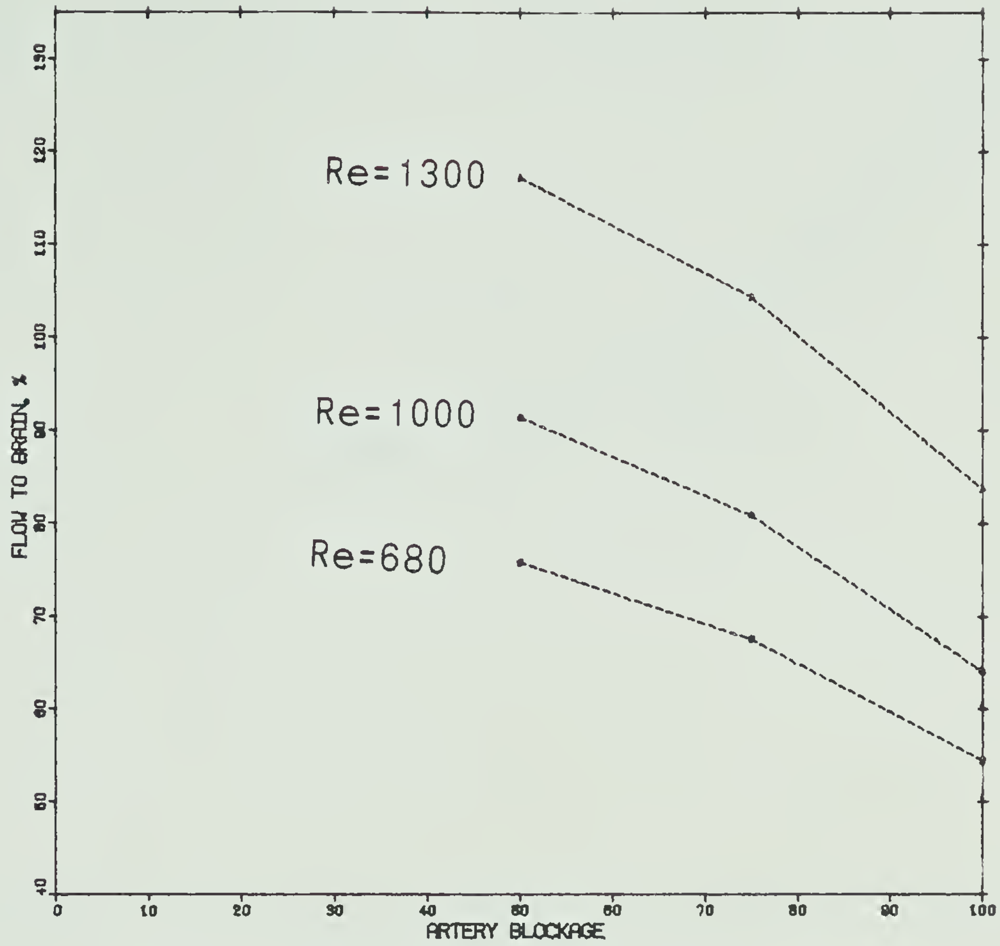

Fig A-9 .. LEFT INTERNAL CAROTID INVOLVED ONLY

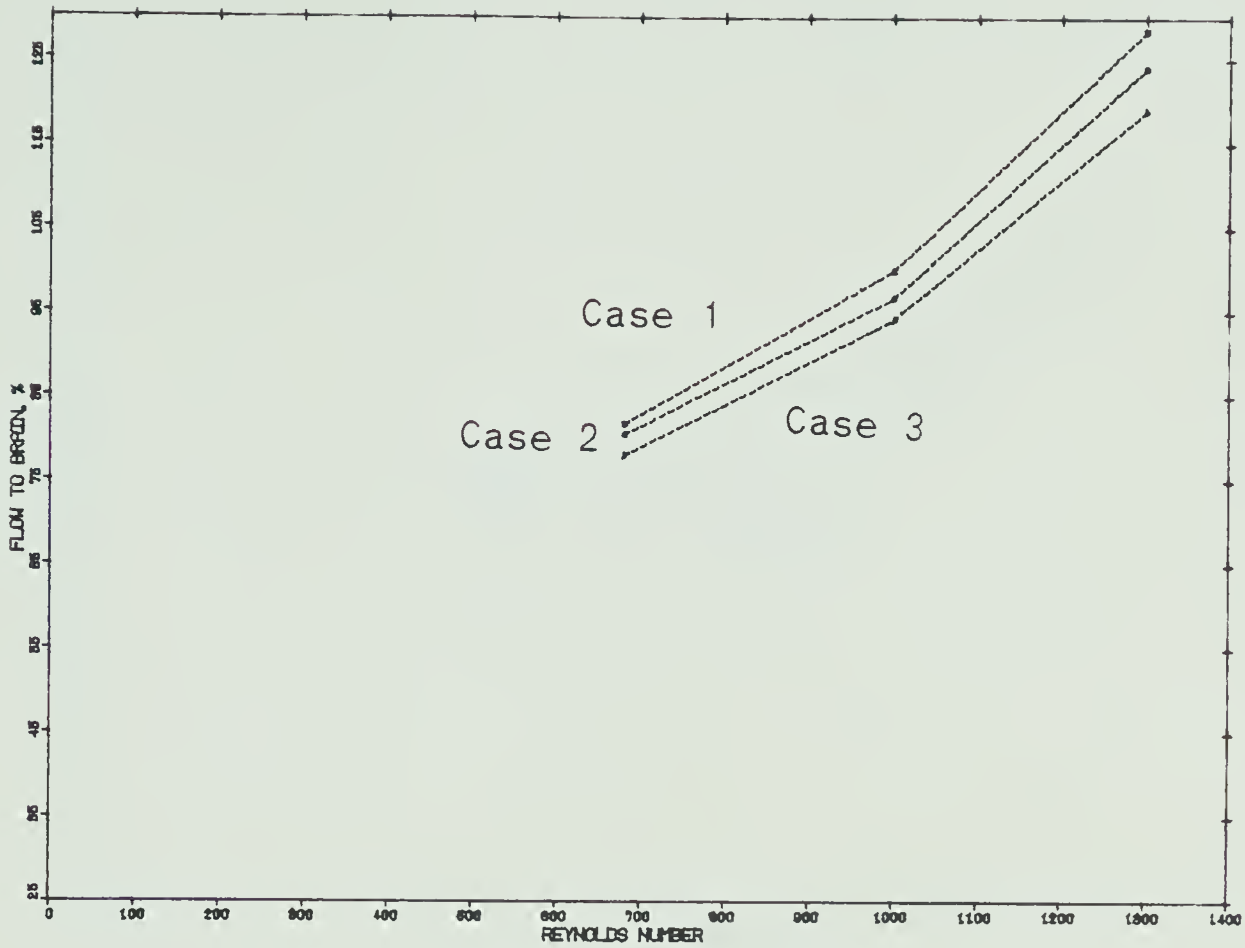

Fig A-10 .. CASES 1 TO 3

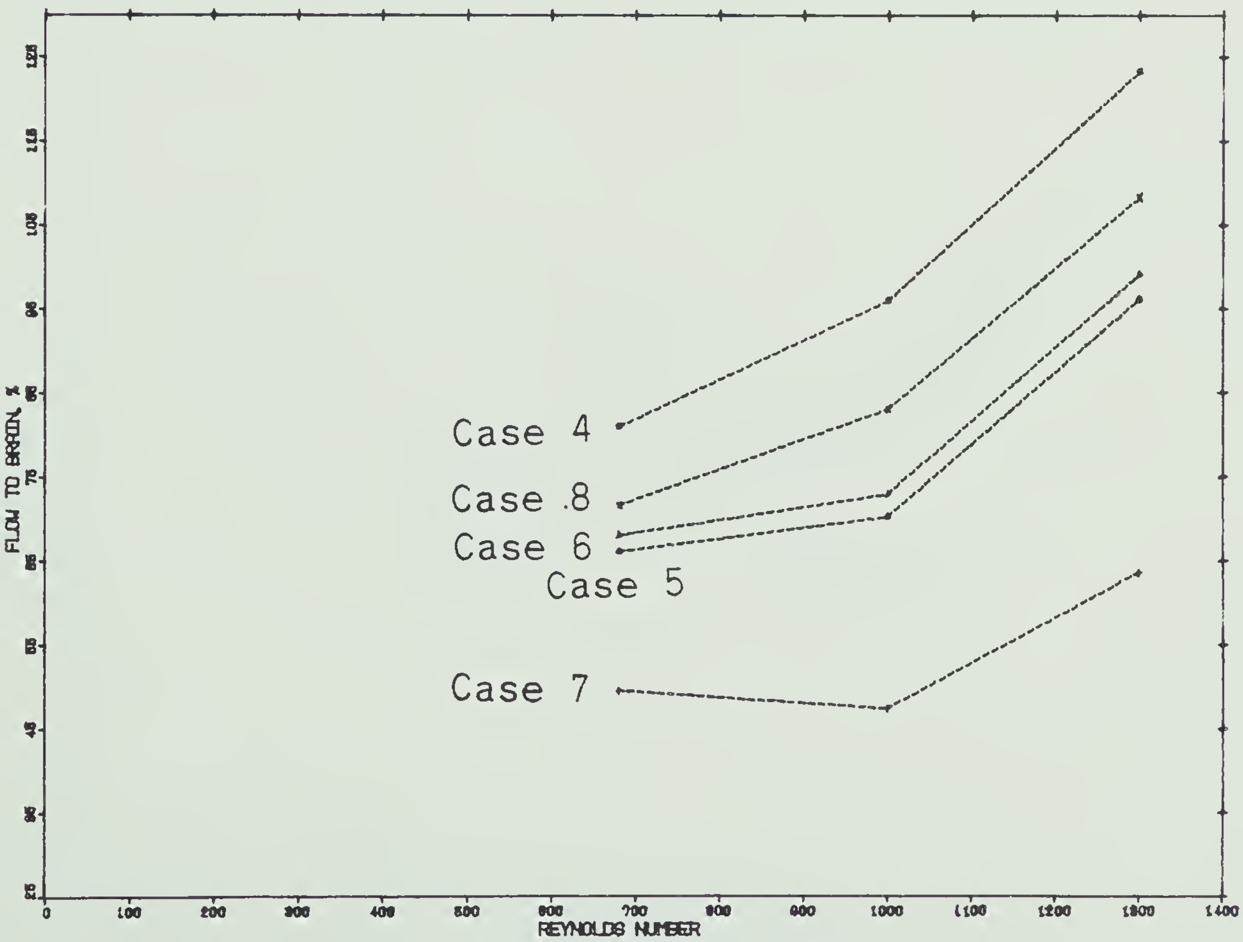

Fig A-11 .. CASES 4 TO 8

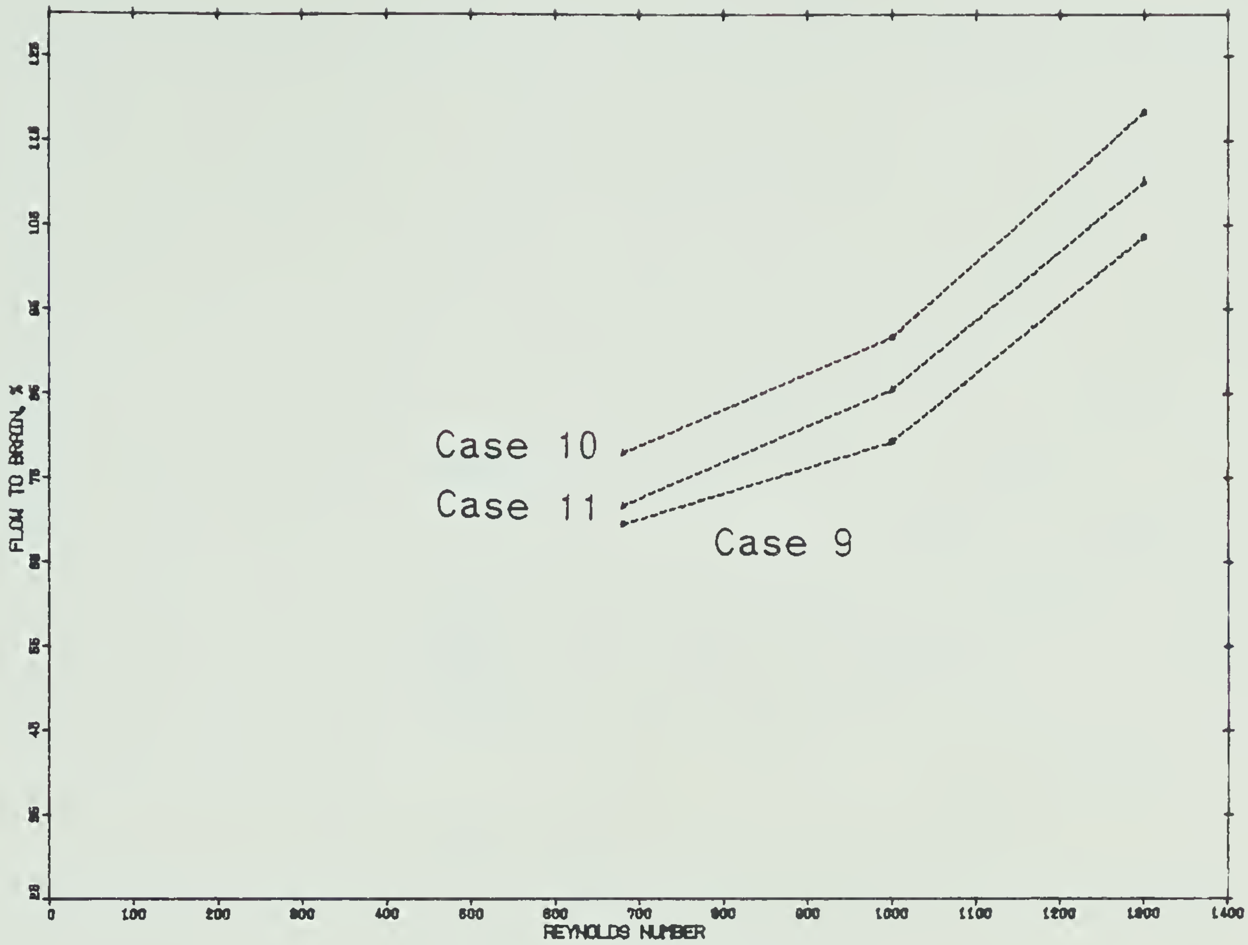

Fig A-12 .. CASES 9 TO 11

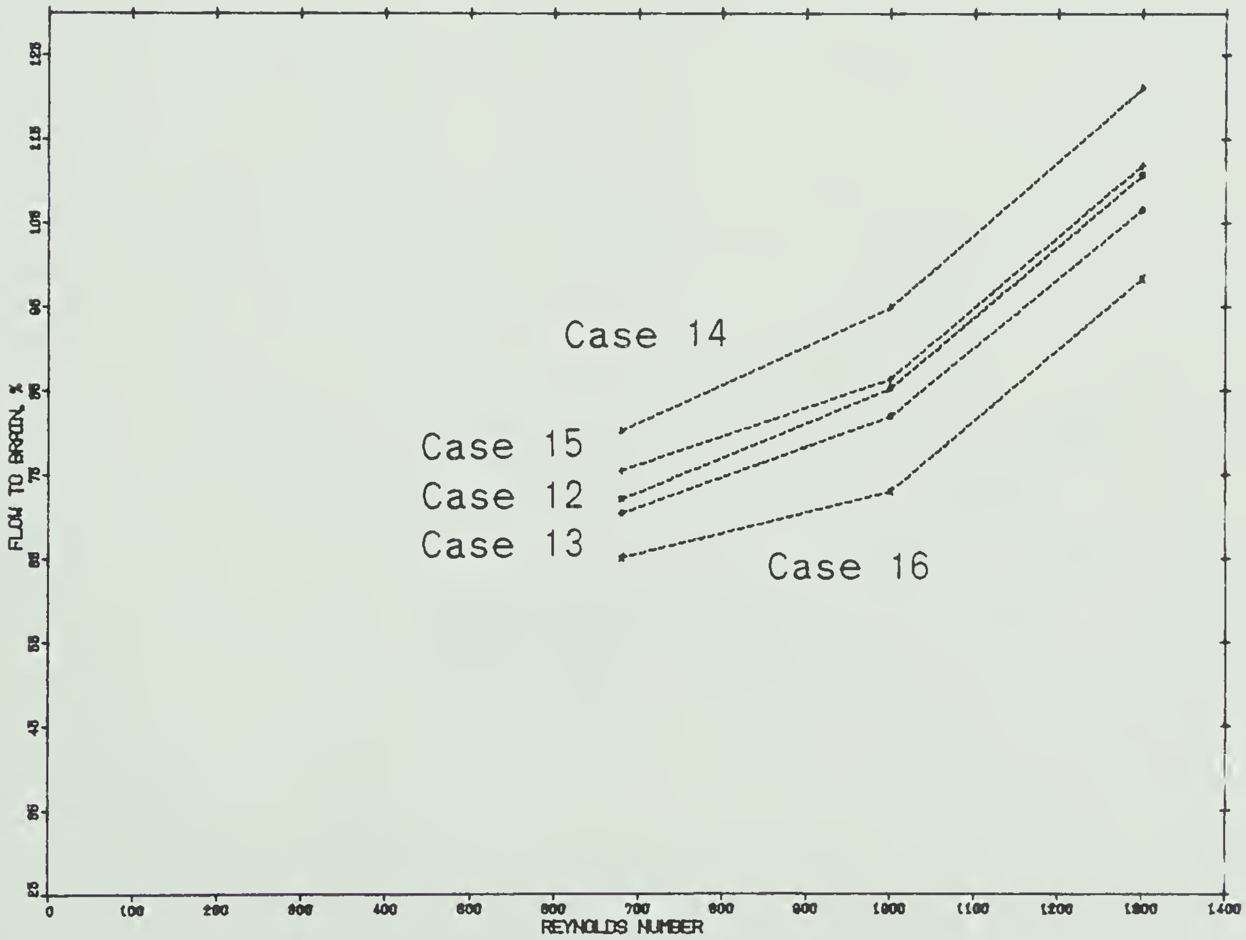

Fig A-13 .. CASES 12 TO 16

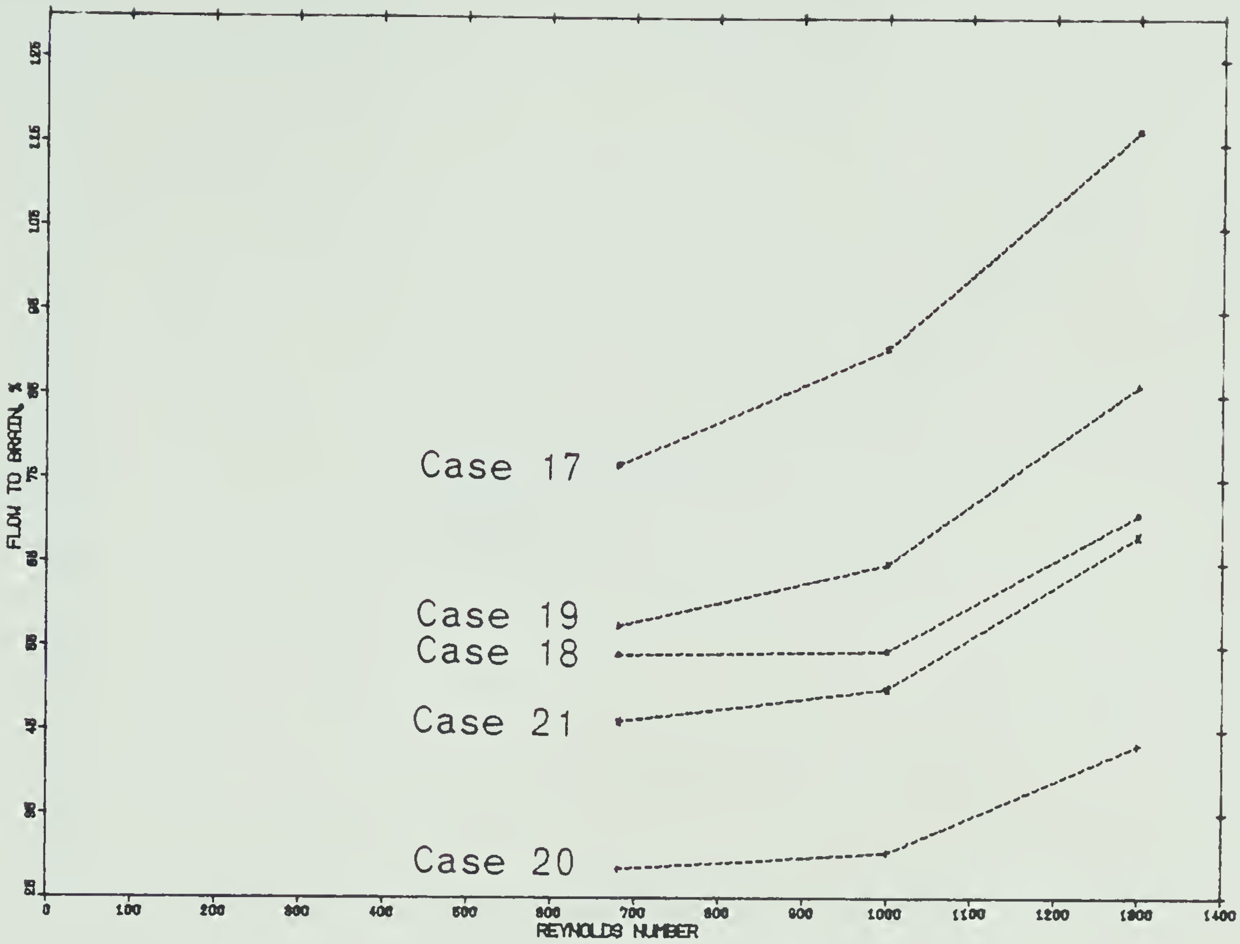

Fig A-14 .. CASES 17 TO 21

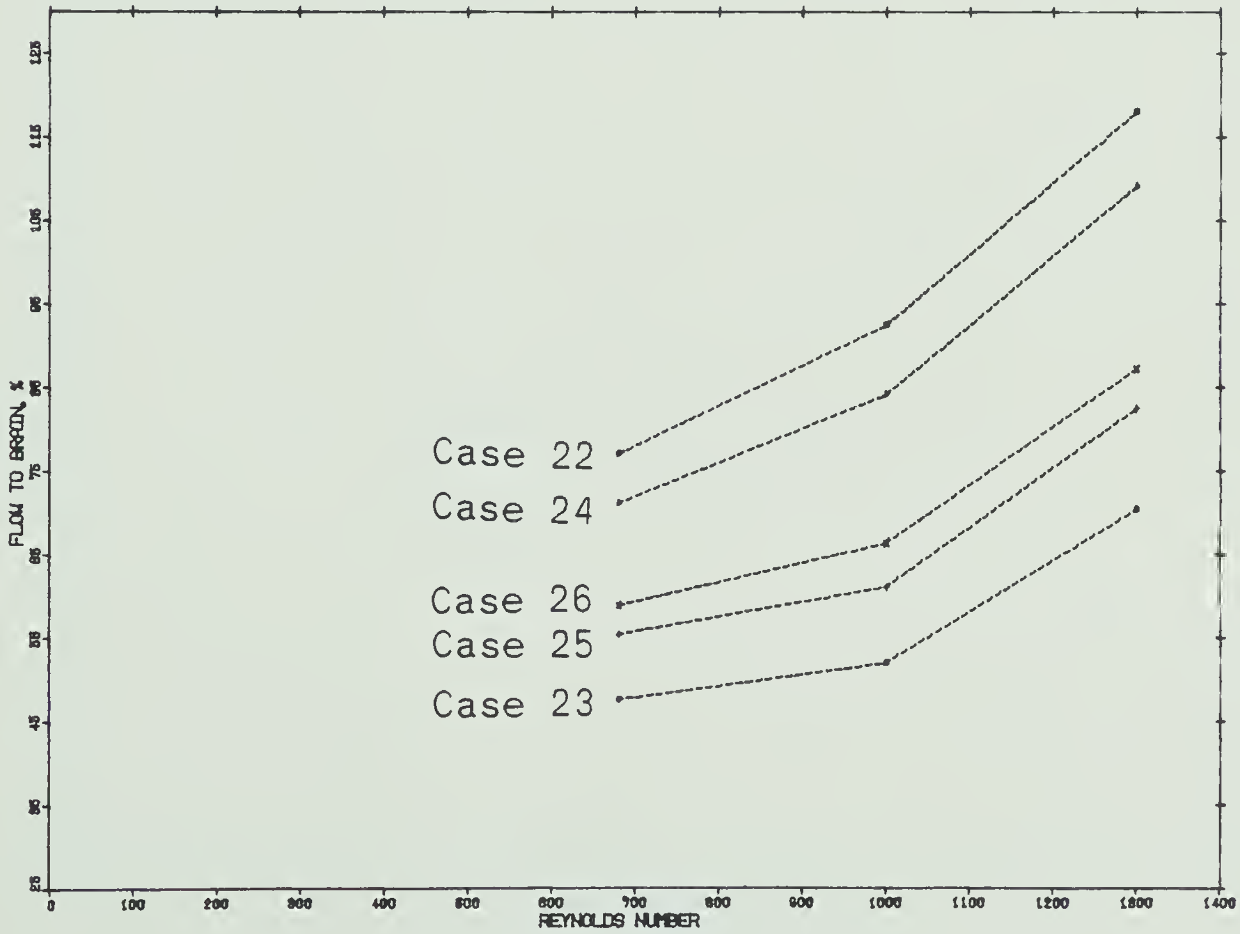

Fig A-15 .. CASES 22 TO 26

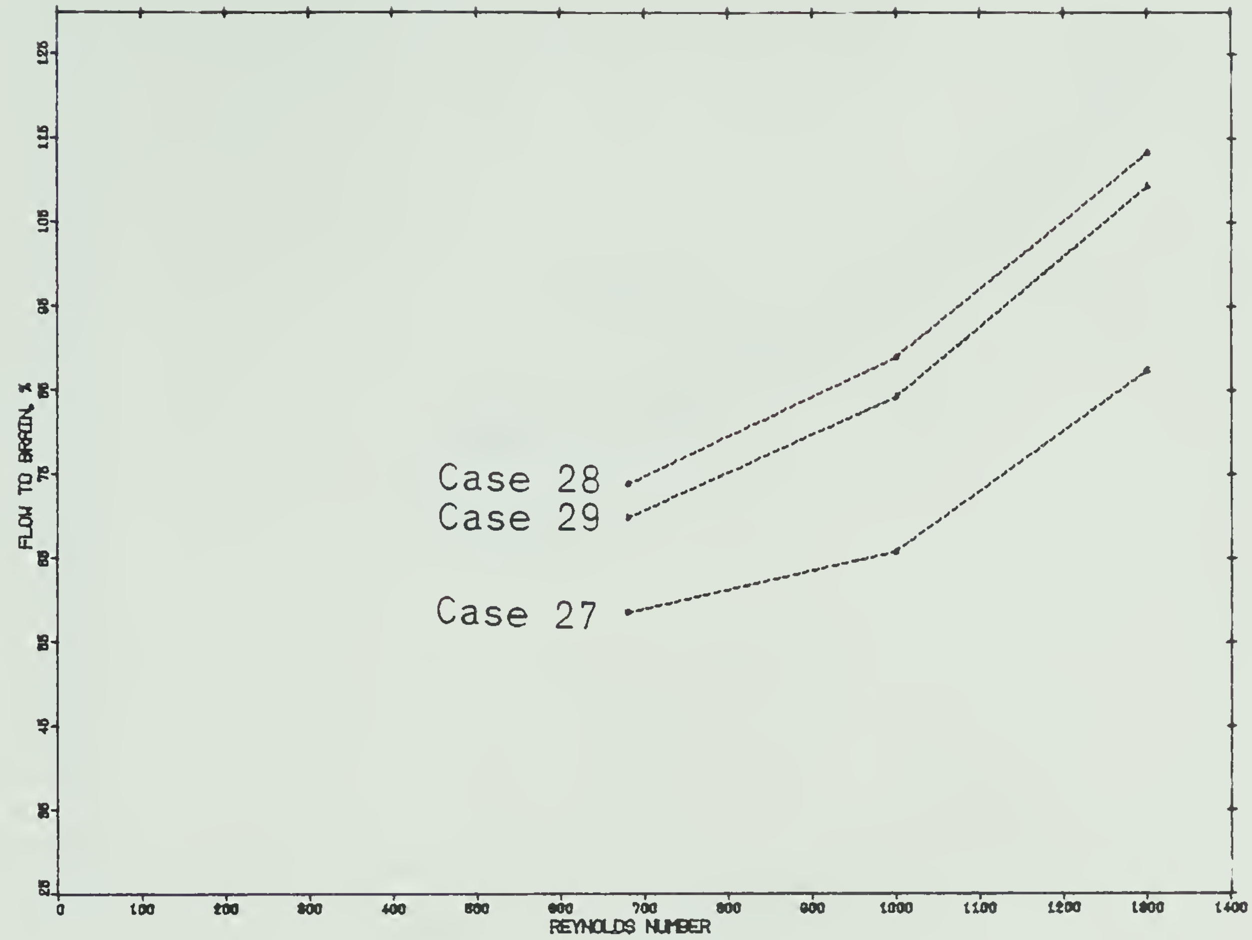

Fig A-16 .. CASES 27 TO 29

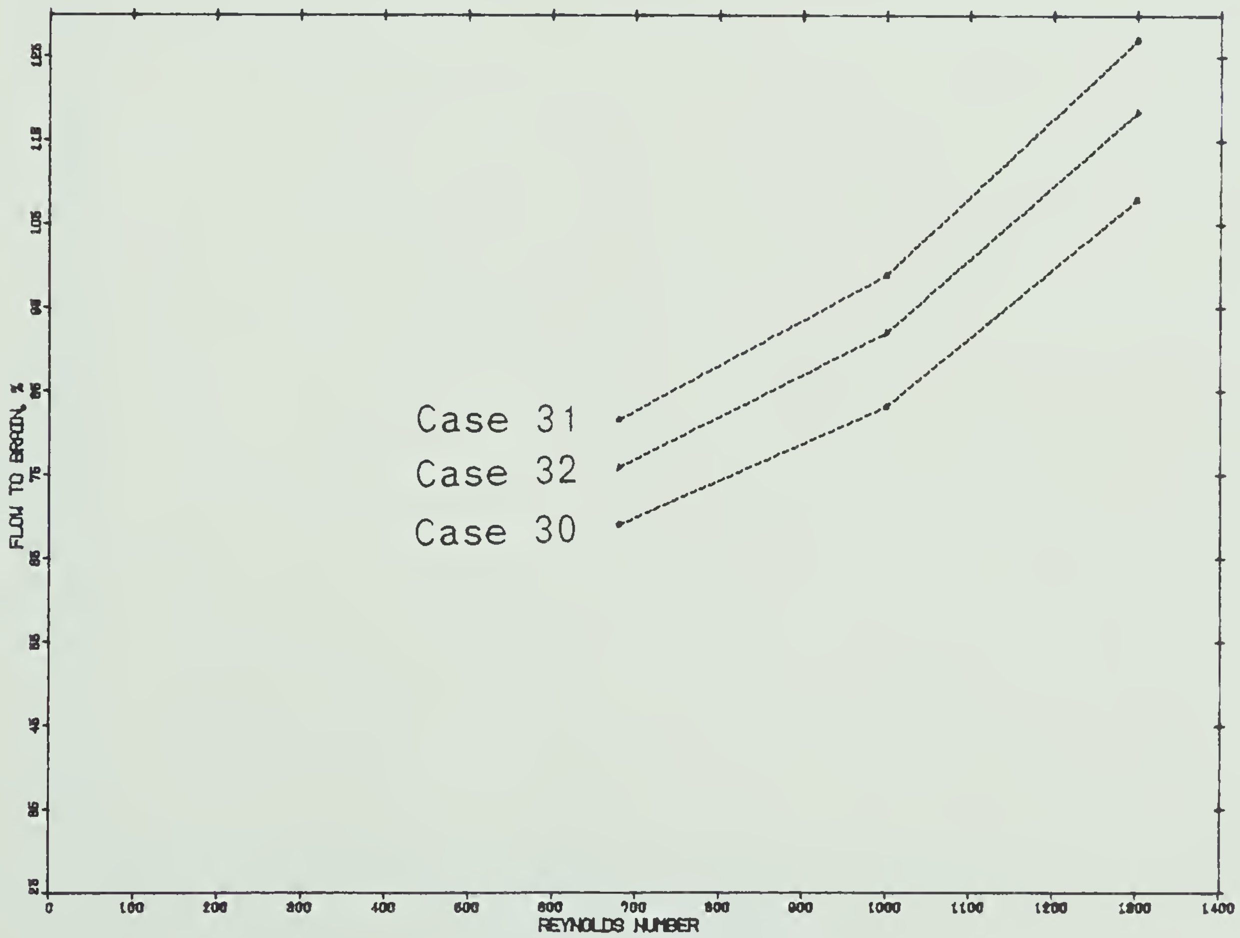

Fig A-17 .. CASES 30 TO 32

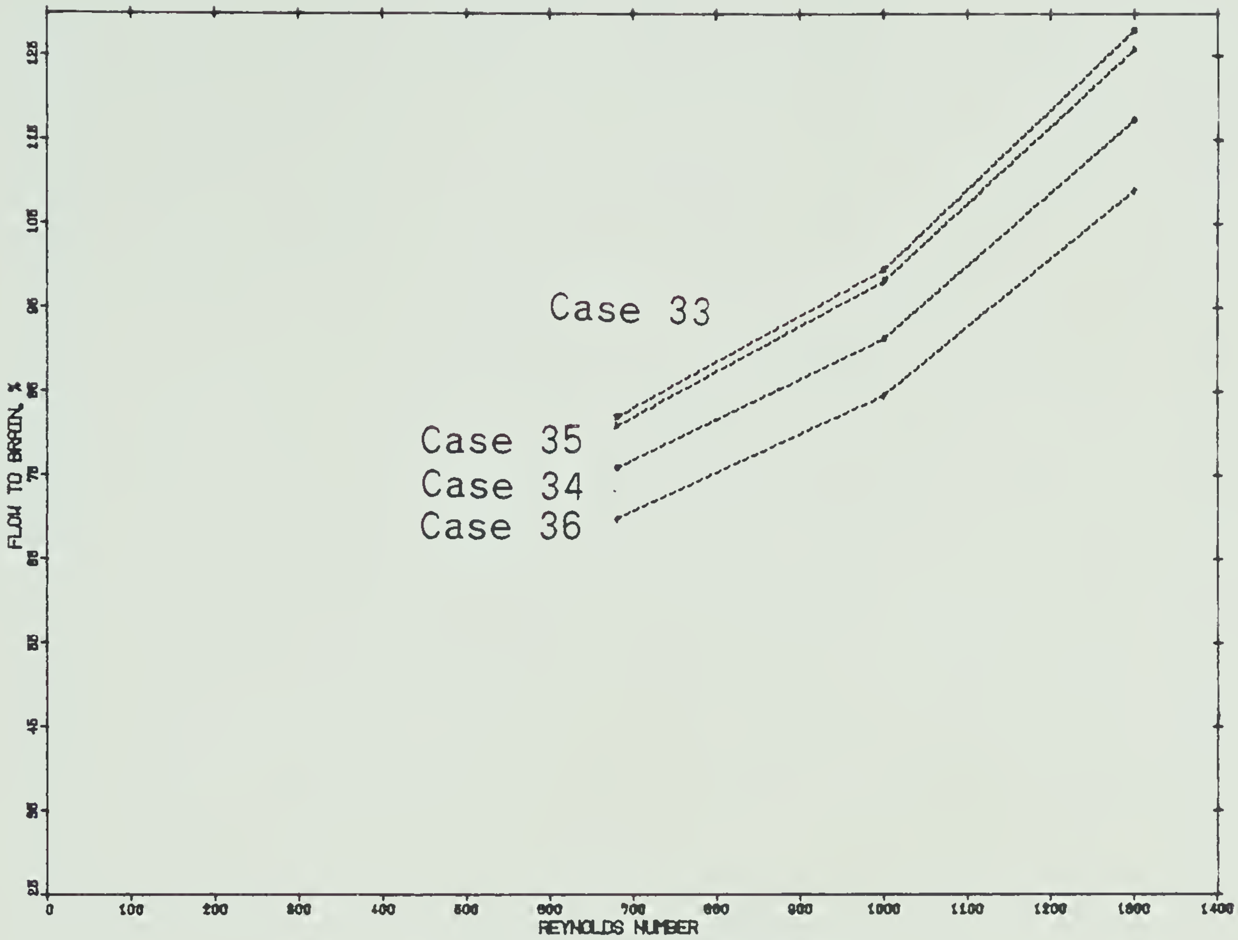

Fig A-18 .. CASES 33 TO 36

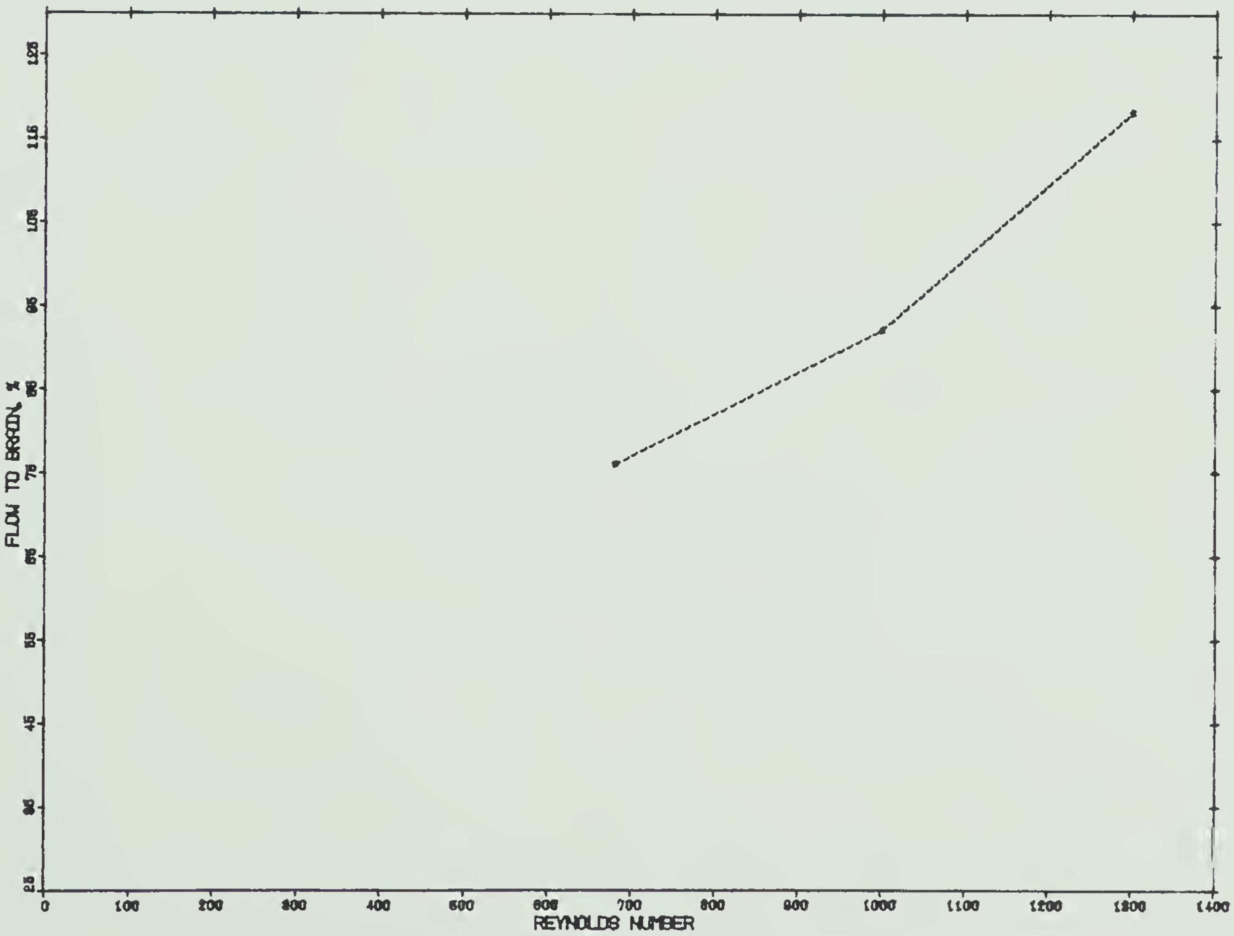

Fig A-19 .. CASE 37

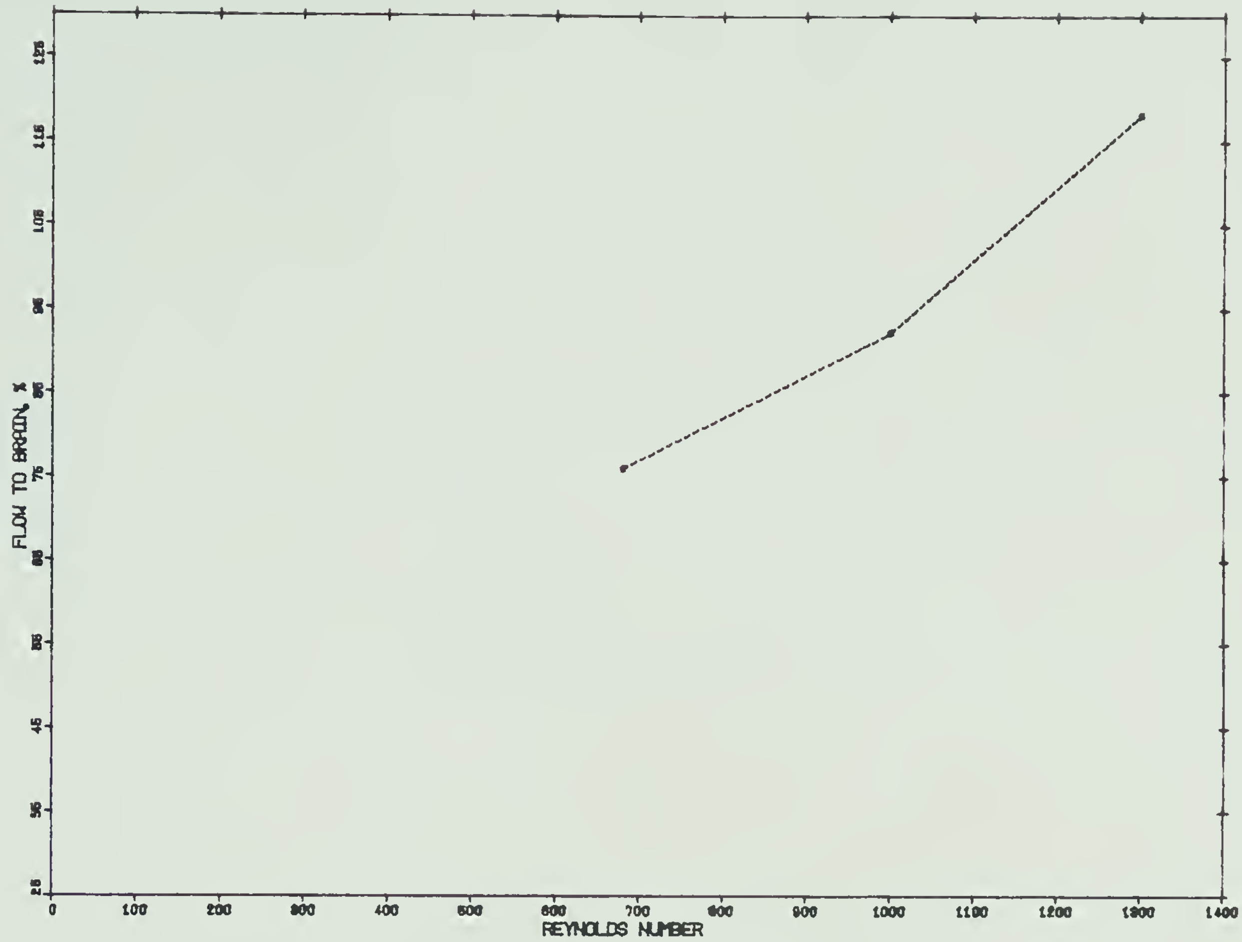

Fig A-20 .. CASE 38

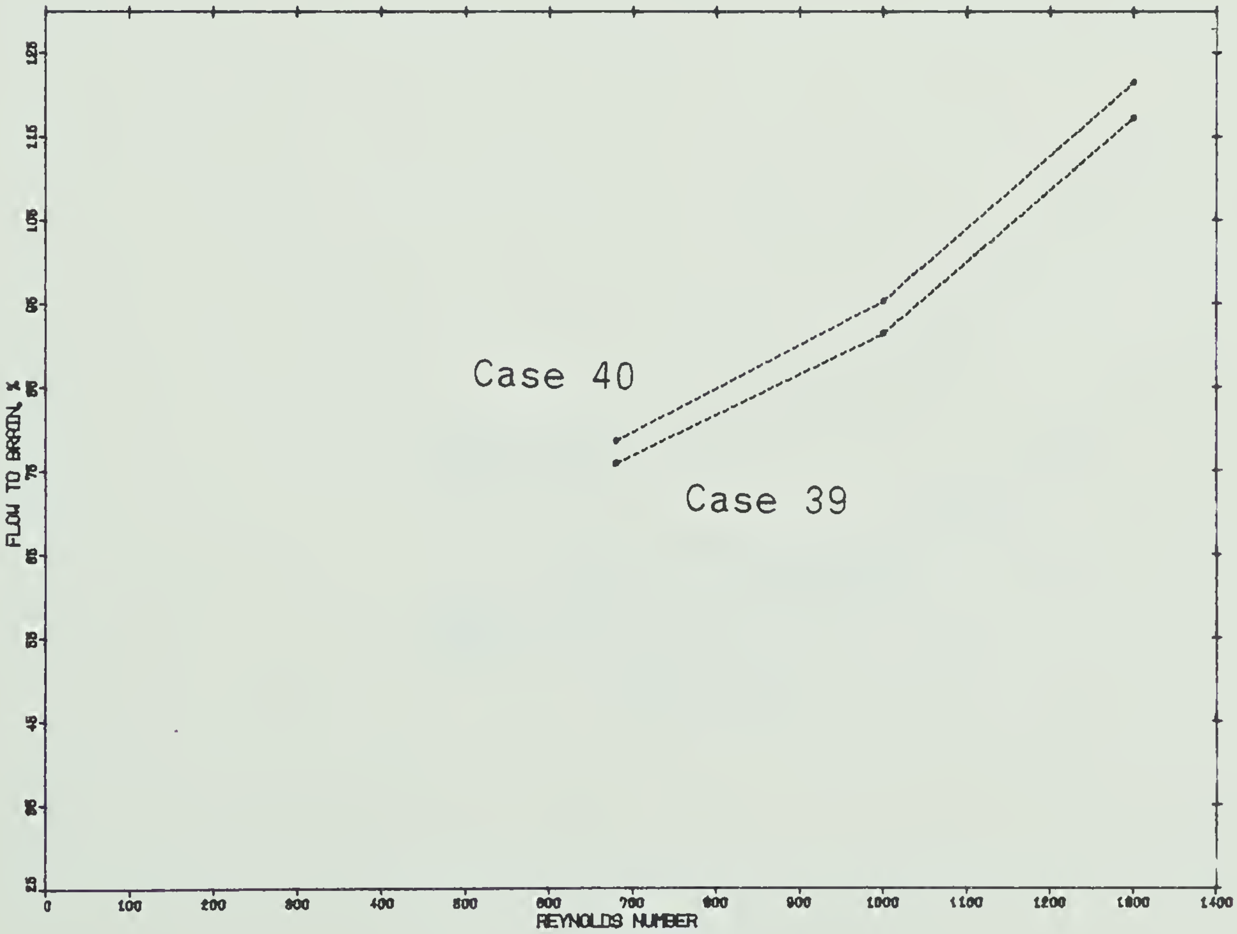

Fig A-21 .. CASE 39 AND 40

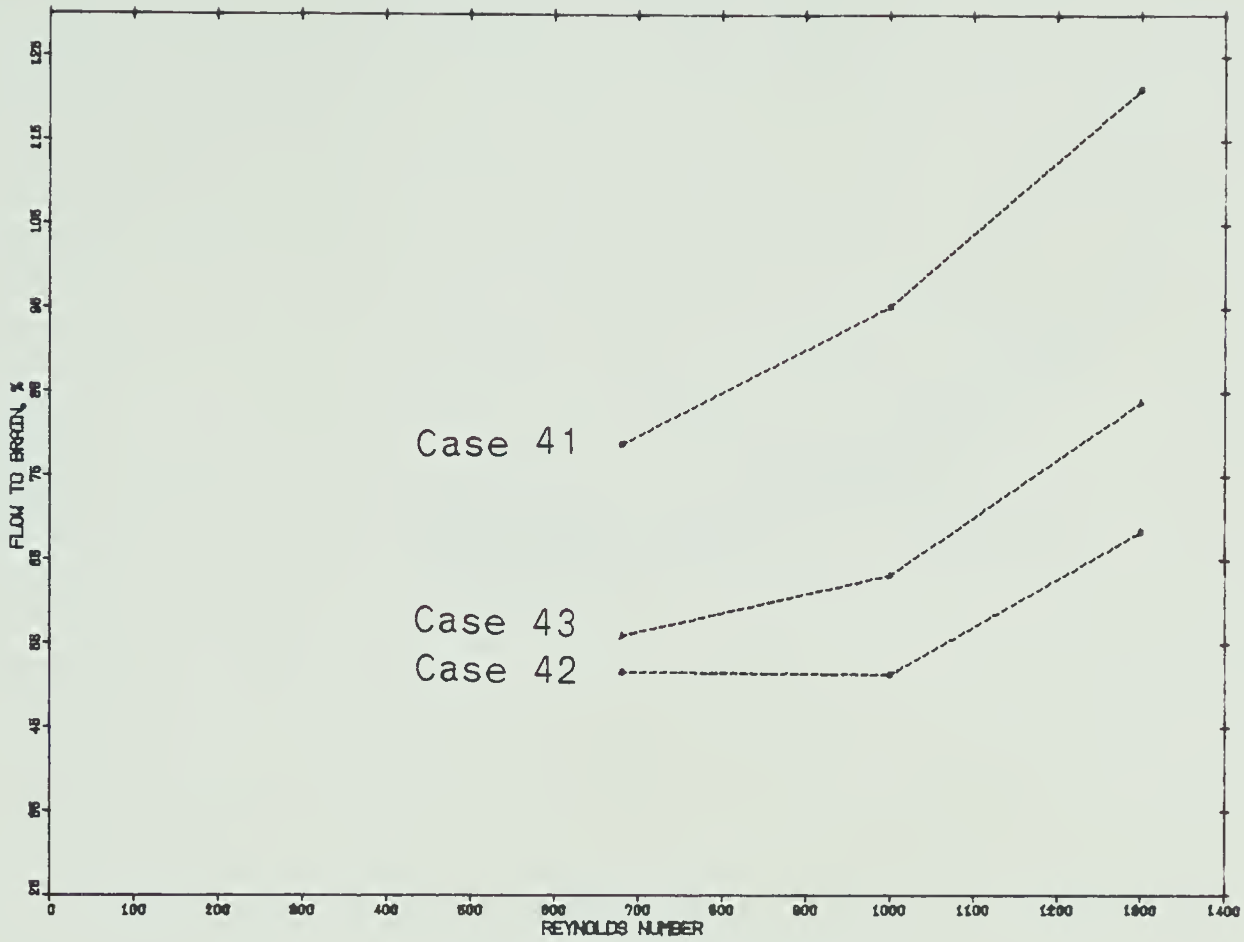

Fig A-22 .. CASES 41 TO 43

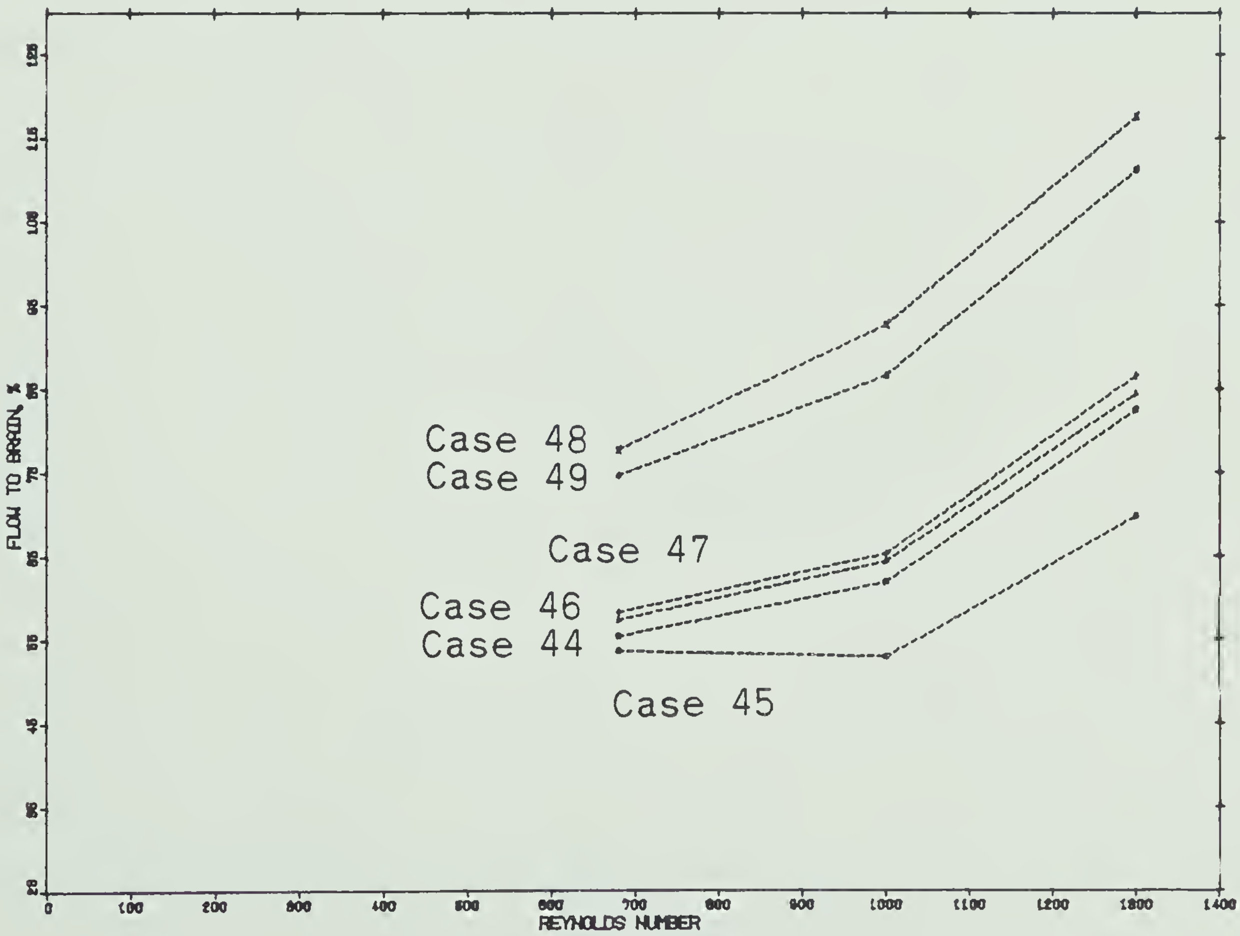

Fig A-23 .. CASES 44 TO 49

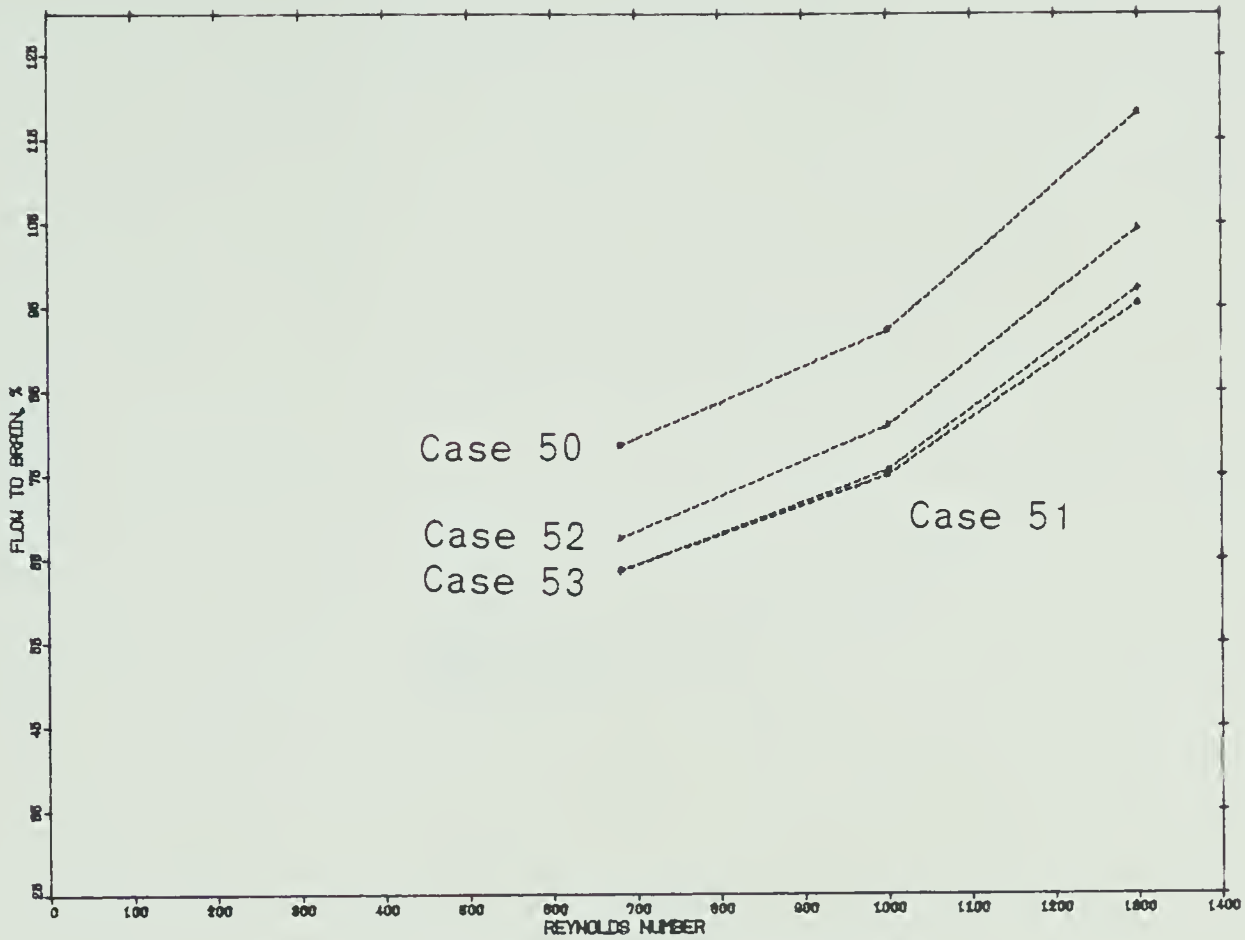

Fig A-24 .. CASE 50 TO 53

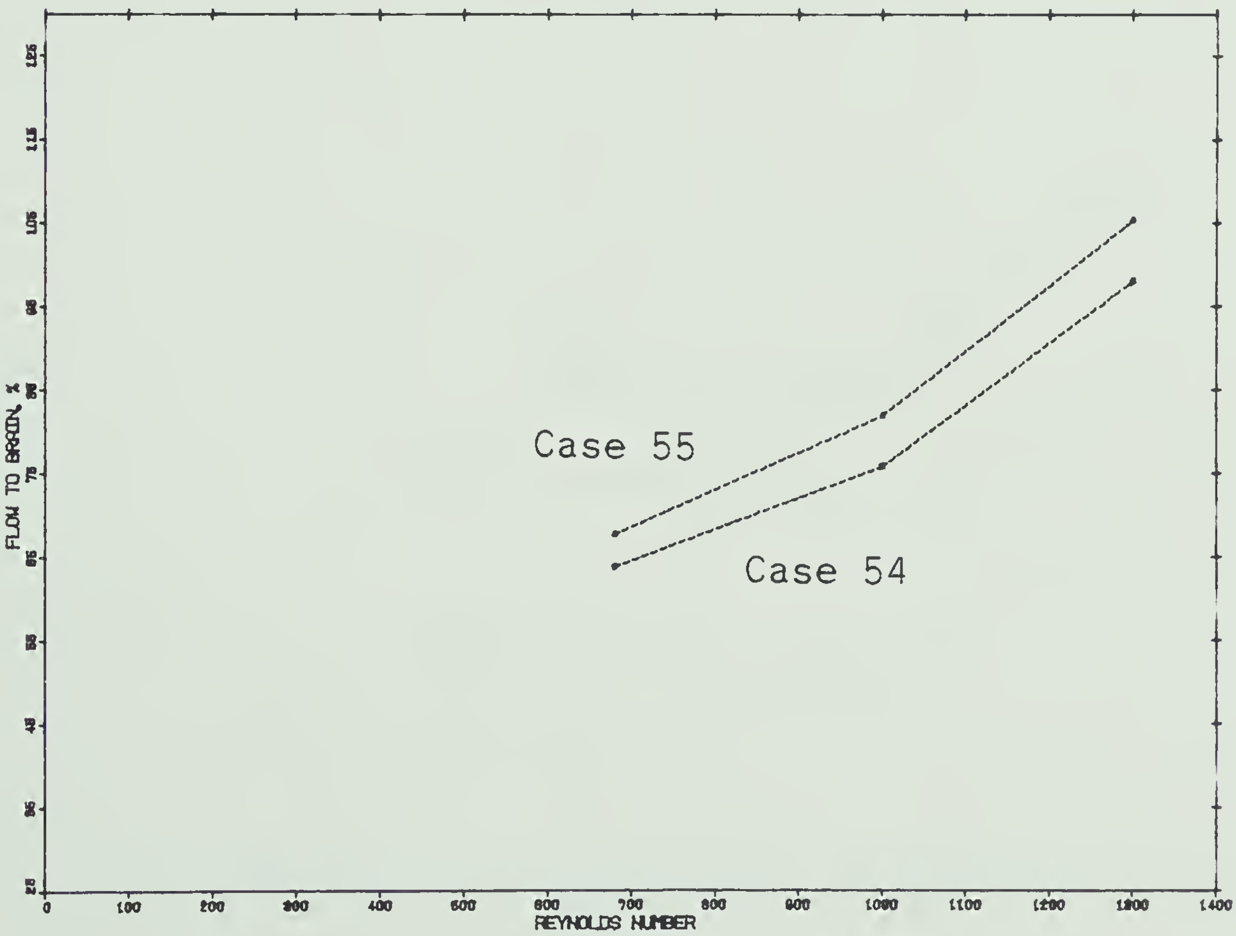

Fig A-25 .. CASES 54 AND 55

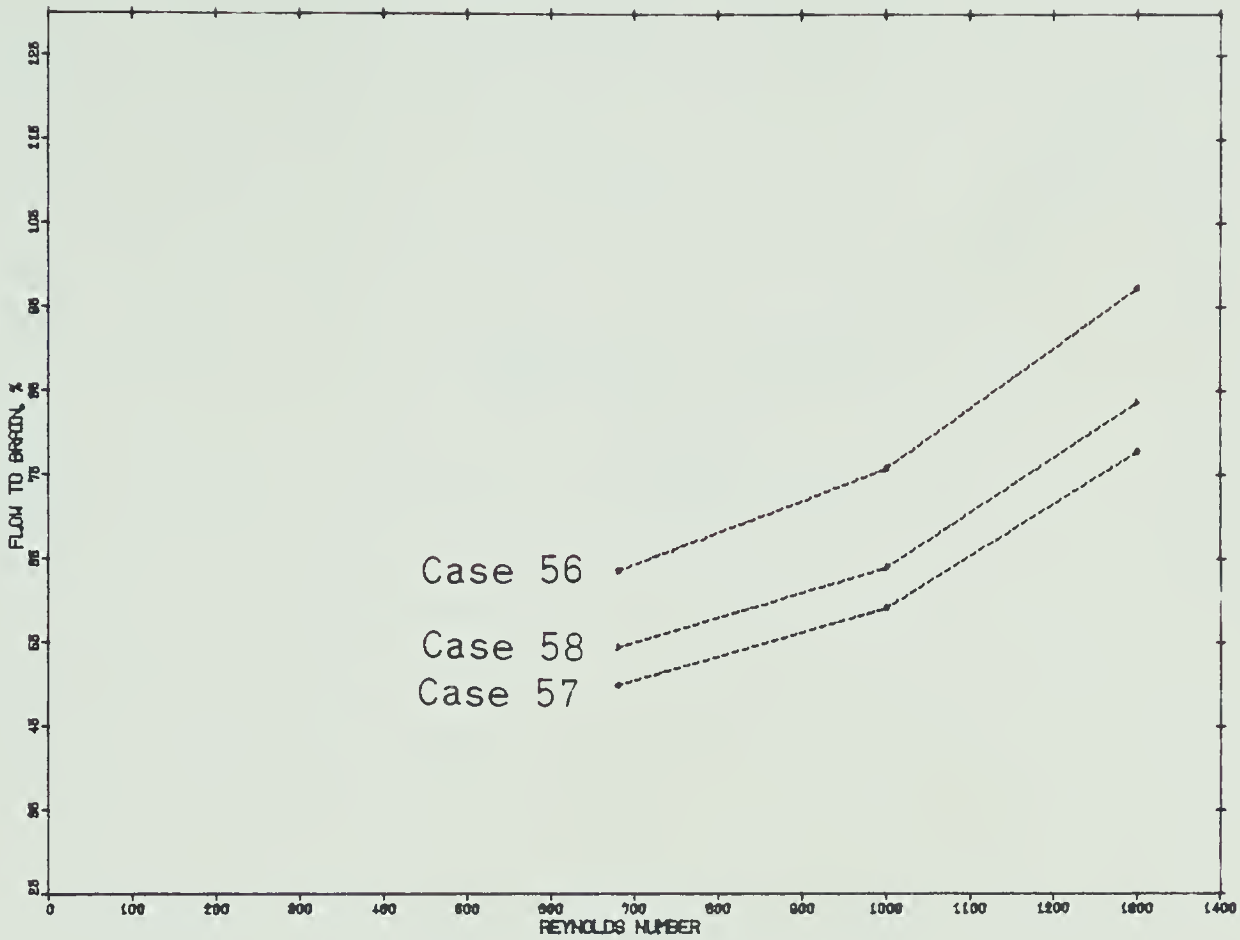

Fig A-26 .. CASES 56 TO 58

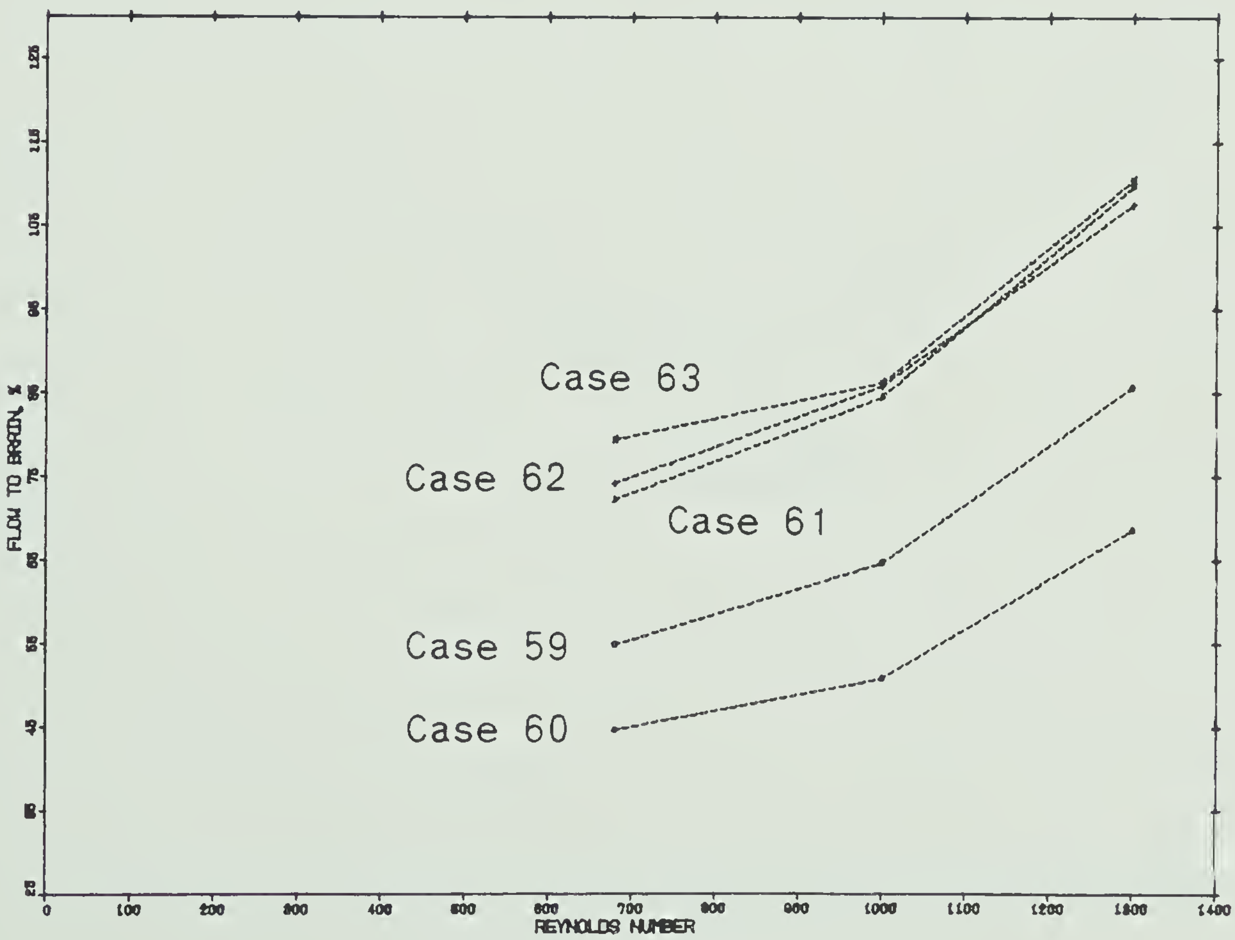

Fig A-27 .. CASE 59 TO 63

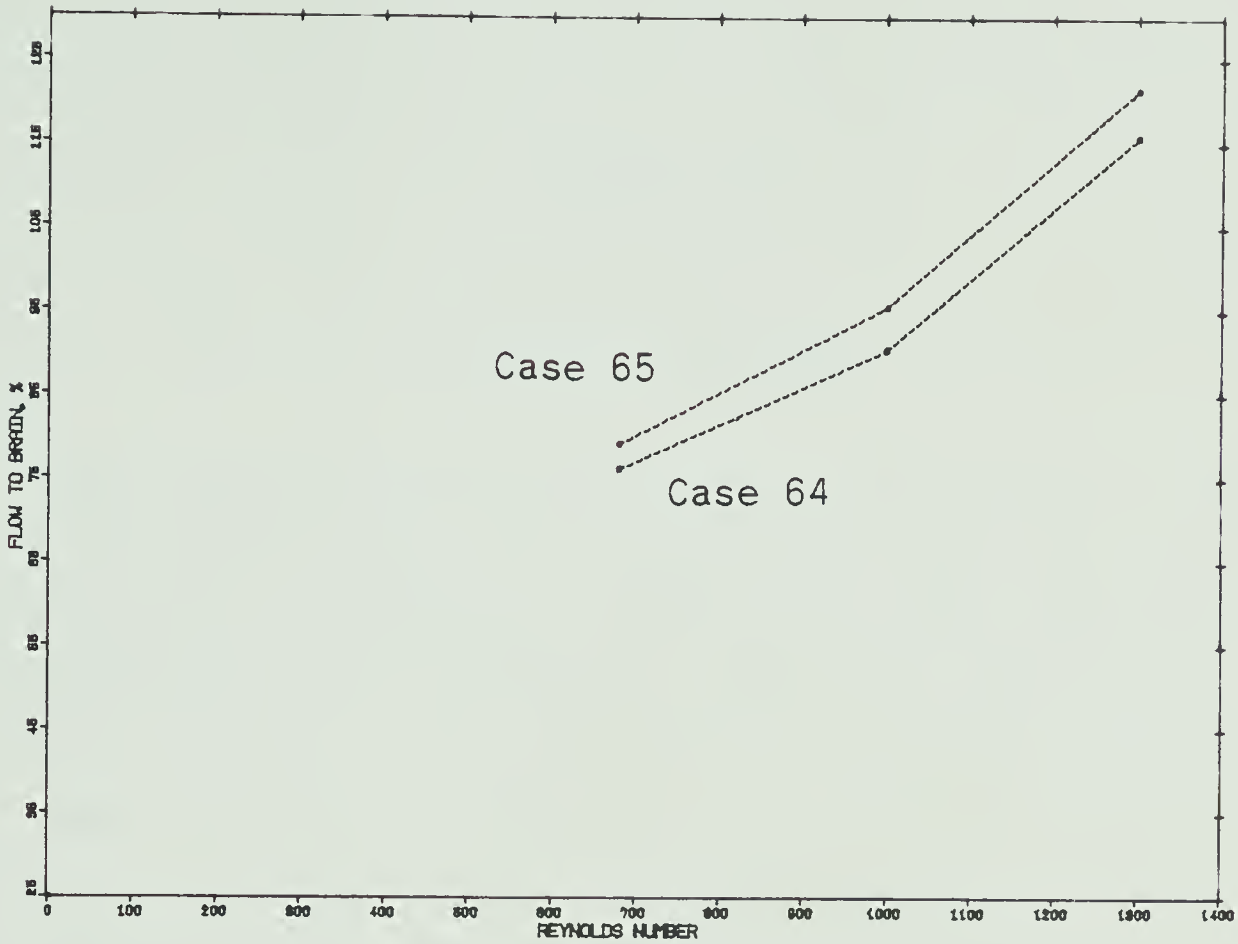

Fig A-28 .. CASE 64 AND 65

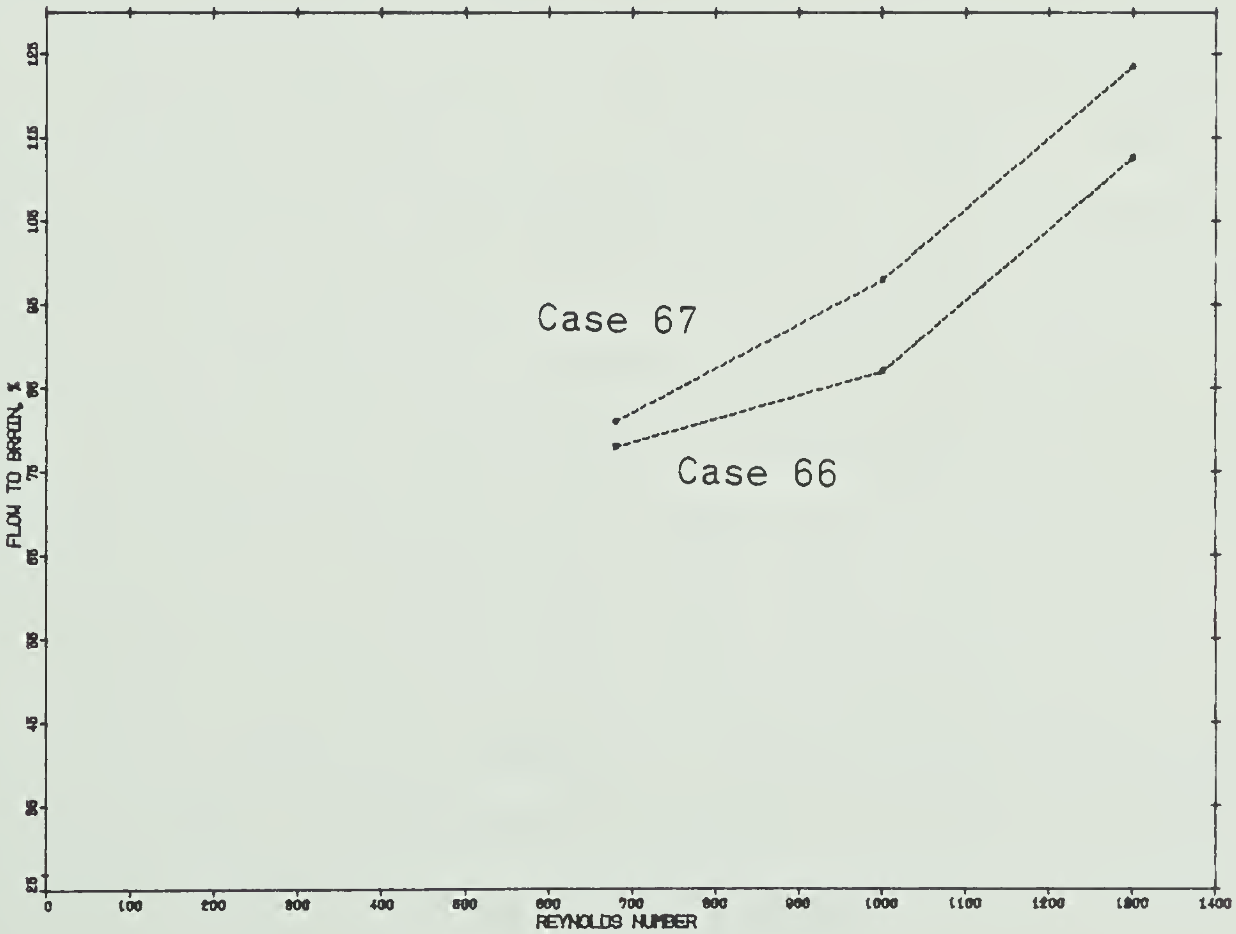

Fig A-29 .. CASE 66 AND 67

APPENDIX B

DESIGN OF THE CAM

The design of the cam was based on the velocity profile as described in Chapter 2. Figure 2.3a shows the actual instantaneous velocity profile at entrance to the aorta whereas Figure 2.3b shows the slightly modified version of the same. Since the piston lies very close to the aortic entrance, the same profile can also be assumed to describe the instantaneous velocity of the piston. Therefore, the profile of Figure 2.3b forms the basis for the cam design.

The profile of Fig 2.3b was graphically integrated, using standard procedures (Jennings and Sidwell, 1968), in order to obtain the displacement profile. This profile described the position of the piston at every instant which determined the required velocity profile at entrance to the aorta. On basis of the volumetric efficiency of the pumping system in which the prosthetic heart valves played the most important role, as determined from experiments, the displacement curve was scaled using a factor of 0.8. The peak of this curve corresponds to the maximum displacement of the piston. A reasonable diameter of the piston was selected (4.8 cm) and the stroke was determined to obtain the required flow rate. The velocity profile was then

scaled accordingly using the polar distance and the pumping efficiency in order to determine the peak and the average velocity at entrance to the aorta for a particular heart rate. These figures are given in Table B-1. The velocity profiles for the three Reynolds numbers are shown in Figure B-1.

The slope of the displacement curve is maximum during the early part of the systole because of the rapid ejection during this period. In other words, the maximum pressure angles were to exist on the cam at points corresponding to the initial period of the cycle. These angles were also anticipated to be extremely high on account of the large slope of the curve. The only way to reduce these angles was to off-set the cam and the follower or to increase the size of the cam. Because of the limitations imposed by the apparatus, the required offset was limited to 1 cm so the only other variable was the cam size. Since a compromise was required between the size of the cam and the pressure angles (too large a cam has problems in precise machining etc. (Jenson, 1965) and it was also not feasible for mounting on the present system), the design value for maximum pressure angles was not limited to the optimum figure of 30°. This relaxation was acceptable considering the slow speed at which the cam was supposed to work, strong follower bearings, sound cam-follower mechanism, low loads and the intermittent operation (Rothbart, 1968). A root diameter of approximately 6 cm gave a cam of reasonable size

TABLE B-1 .. AVERAGE AND PEAK VELOCITIES/REYNOLDS NO (at entrance to aorta)

HEART RATE beats/min	AVERAGE VELOCITY cm/sec	PEAK VELOCITY cm/sec	AVERAGE REYNOLDS NO	PEAK REYNOLDS NO	PERIOD OF SYSTOLE sec
50	9.85	65	680	4500	0.350
70	14.33	90	1000	6240	0.250
90	18.87	116	1300	8040	0.194

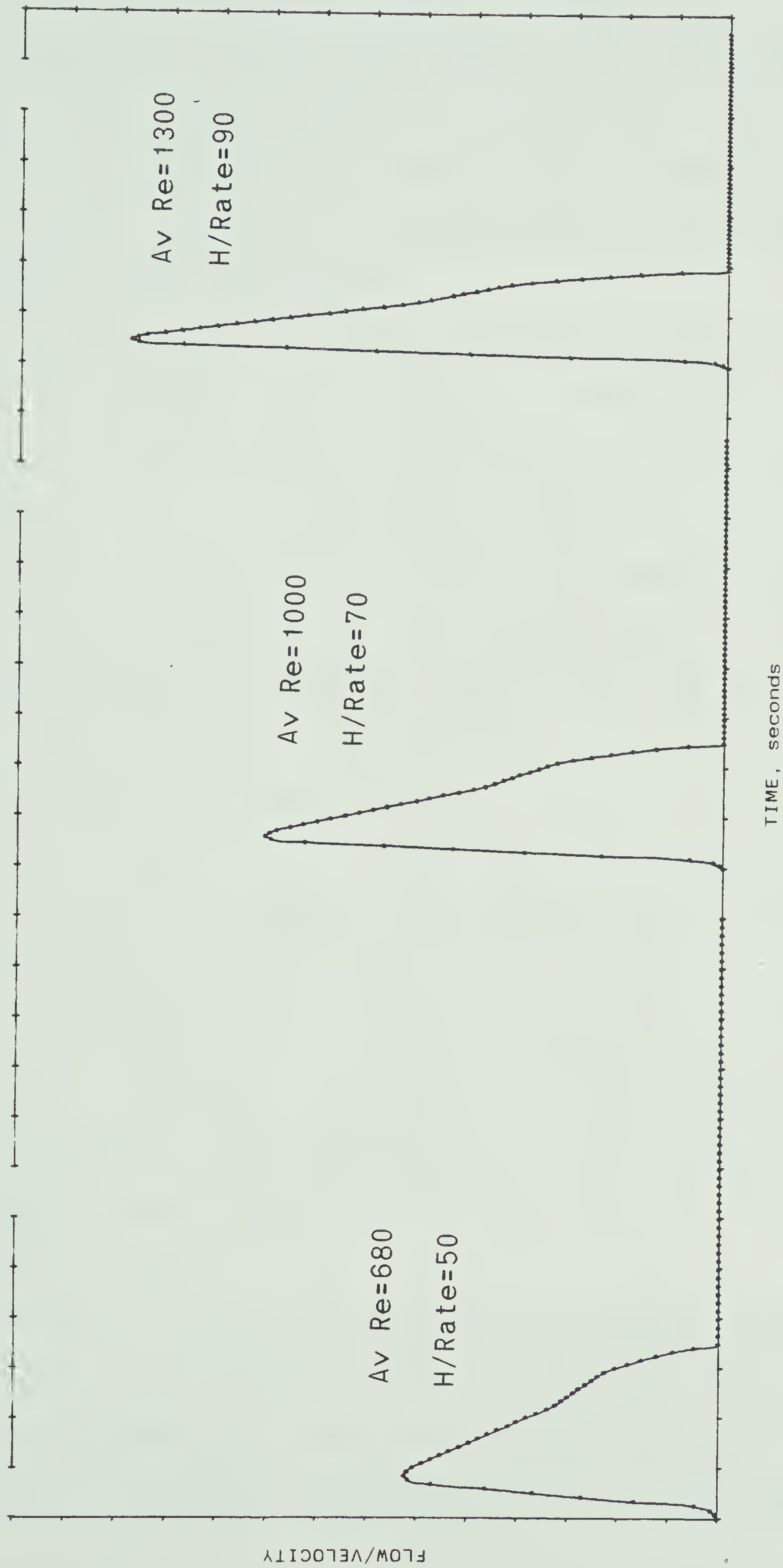

FIG B-1 .. VELOCITY/FLOW PROFILES AT VARIOUS HEART RATES

with the maximum pressure angle limited to 37° at the point corresponding to the maximum slope of the displacement curve. Under these conditions, the cam was found to work smoothly and without any excessive wear throughout the experiments. There was no damage done to the bearings or the cam-follower mechanism.

In order to obtain the cam profile, a circle equal to the pitch diameter (root diameter of the cam plus the diameter of the follower) was drawn and divided into intervals of 5°. The position of the piston was marked at each point in accordance with the displacement curve obtained by integration of the velocity profile. At points of rapid change of slope the interval was reduced to 2.5° for higher accuracy. All the points thus obtained, when joined, gave the pitch profile of the cam i.e. the path on which the centre of the follower was expected to travel.

The ejection phase of the cardiac cycle constitutes about 30 percent of the total stroke period (0.25 seconds at the normal pulse rate) and this corresponds to 105° of cam rotation. Therefore, this portion of the pitch profile was determined with high precision as the remainder of the cycle was merely meant to refill the left ventricle for the next systolic action.

The position of the follower was drawn at every point (2.5°/5.0°) on the pitch profile as obtained above. The internal tangent to these positions dictated the inner contour of the groove cam whereas the external tangent

determined the outer contour. Two steel templates were cut in accordance with these profiles and were properly positioned on a teflon disc with dowel pins. The groove for the follower was then machined so that it followed the exact profile as determined above. Figure B-2 shows the profile of the cam (not drawn to scale).

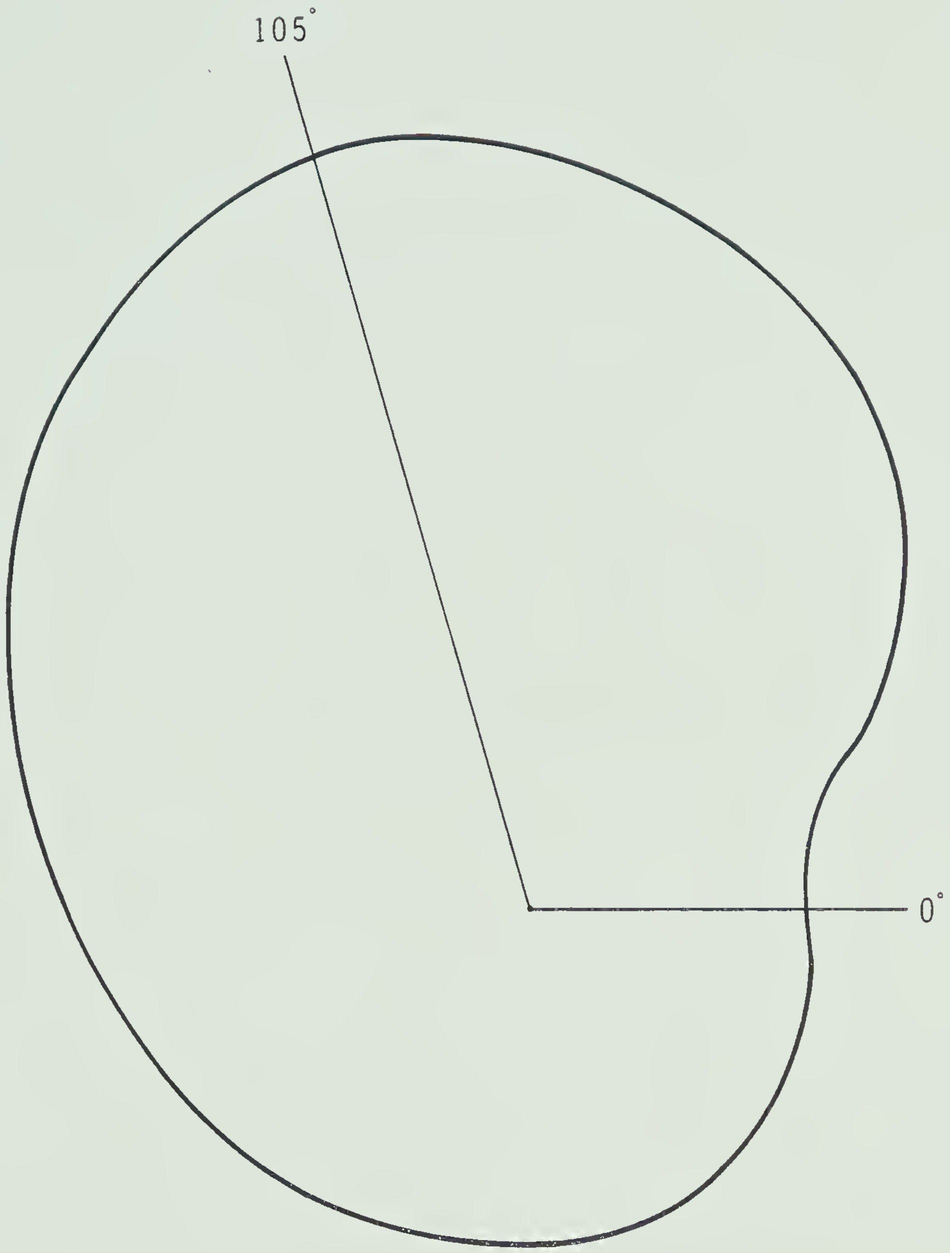

FIG B-2 .. PROFILE OF THE CAM

Not to scale