Prediction of arterial compliance from pressure and flow waveforms

by

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1 INTRODUCTION

Compliance is a term frequently used to describe in a vague, general sense how the geometry of an elastic material changes when an external pressure is applied. For example, a dolphin swimming in the ocean induces flow over a surface which has compliance, *i.e.*, the dolphin's skin is a complicated elastic material which can deform under the pressure of the surrounding sea water. In the case of fluid flowing through a conduit or tube, the effect of transmural pressure across the walls of the tube depends on the compliance of the tube material.

More specifically, arterial compliance refers to the increase in cross-sectional area of an artery caused by an increase in transmural pressure. Transmural pressure is the difference between the internal and external pressure across the wall of an artery. In the body, this increase in transmural pressure can be understood from some basic knowledge of physiology and hæmodynamics. Consider, for instance, what happens when blood is pumped from the left side of the heart and enters the aorta. During the systolic phase of the heart cycle, the heart undergoes an isovolumic contraction during which the walls of the ventricle contract but the valves remain closed so that the blood cannot escape. Since blood is an incompressible fluid, the pressure in the left ventricle rises. When the pressure in the ventricle becomes greater than that in the aorta, the aortic valve opens and blood flows into

the aorta. Because of the high peripheral resistance, blood enters the aorta faster than it leaves, and there is an increase in transmural pressure. To accommodate this increase, the arterial walls expand causing an increase in the cross-sectional area of the vessel. Since ventricular systole only accounts for approximately one-third of the cardiac cycle (Ganong, 1985), there needs to be a mechanism such that blood will be delivered to the capillary beds in a less variable fashion than that produced by the heart alone. This mechanism arises from the compliance of the arterial wall, and the smooth muscle in the arterial wall. The compliance gives the arterial system its capacitance enabling blood to be stored in the large arteries during systole. Then, during diastole, stretch receptors in the arterial walls trigger the smooth muscle to cause the volume of the lumen to decrease and the blood to be squeezed through the circulation (Dobrin, 1974). This makes the flow to the capillaries more steady than the flow coming directly out of the heart. Hence, if there is a change in the elastic properties of the arterial walls, the normal flow and pressure waveforms may become altered. Therefore, compliance is important not only to the arteries themselves, but also can have a dramatic effect on the blood flow to the organs they supply.

Compliance is a measure of the elasticity of a material. In solid mechanics, elasticity is described using the modulus of elasticity, E, having dimensions of force per unit area. Since the relationship between stress and strain for an arterial wall is highly nonlinear (Hasegawa and Azuma, 1979), it is more useful to define an incremental modulus of elasticity, E_{inc}, that is valid over a small region of varying pressure. Compliance is inversely proportional to E_{inc}; i.e., a high value of E implies

low compliance or a *stiff* artery. Thus, compliance can also be thought of as a measure of the distensibility of the arterial wall. The modulus of elasticity increases with increasing transmural pressure, which means that the arterial wall becomes less distensible (less compliant) with increasing intralumenal pressure (Papageorgiou and Jones, 1987).

From a clinical perspective, changes in arterial compliance can be manifestations of many disease states. For example, it has been well documented that the calcified plaque residue which accumulates on the walls of many large arteries during atherosclerosis causes the arterial wall to become less elastic thus causing a measurable decrease in compliance. Also, blood flow through stenoses can be affected by the compliance of the stenotic region. Subintimal hyperplasia, which is an abnormal increase in the number of normal cells in normal arrangement below the intimal layer of the arterial wall, also causes a change in arterial compliance. In addition, aneurysms can result from sustained high transmural pressure and enlarged lumenal diameters. Invoking the law of Laplace, $T = pr$ where T is the wall tension, p is the transmural pressure and r is the mean vessel radius, we see that increasing p or r results in a corresponding increase in the wall tension. With time, this can cause the arterial wall to become weak and possibly burst (Dobrin, 1984). Early manifestations of these various disease states could possibly be determined from changes in arterial compliance. It is also known that compliance tends to decrease with age (Kinley and Marble, 1980) and compliance decreases peripherally (Nicolaides, 1985). Thus, changes in arterial compliance are of interest to many clinicians and can have many clinical applications. In fact, the knowledge

of a change in arterial compliance is often of much greater value than the actual value. For instance, at birth, leg arteries appear to be markedly more compliant than the aorta. Relative values are reversed in the first five years, after which the aorta remains more compliant, reaching a maximum value around ten years and then decreasing sharply towards leg values until 20 years. Beyond this age aortic compliance decreases very slowly, and aortia, iliac and leg arteries appear to tend towards equal compliance in the sixth decade (Laogun, 1982).

Compliance is also important in the design and choice of artificial vascular grafts. If a section of material is anastomosed to an intact artery, whether the material is natural or synthetic, the compliance of the two pieces is likely to be different. If this difference is great, a phenomenon called compliance mismatch can exist (Hasson, Megerman and Abbott, 1985). In this situation, as blood flows through the anastomosed region, the change in cross-sectional area due to the changing transmural pressure will not be identical on both sides of the region. This causes an uneven stress distribution at the anastomosis, possibly resulting in suture-line failure and the formation of an anastomotic aneurysm (Mehigan, Fitzpatrick, Browne and Bouchier-Hayes, 1985).

Although compliance is recognized as an important arterial characteristic, it is not easily measured. Thus, the goal of this research has been three-fold:

- Develop a technique for measuring arterial compliance using pressure and flow waveforms.

- Design an automated process capable of repeatedly measuring compliance with little or no input from the operator.

- Investigate the feasibility of the technique by measuring the compliance of flexible tubes, including segments of arteries.

It is important to point out the collecting large amounts of data was *not* an objective here. Rather, only a small set of data was collected to determine the feasibility of the technique.

2 LITERATURE REVIEW

There have been a number of different techniques used to measure compliance. Before reviewing prior studies, it is of interest to define the term compliance and develop some criterion to classify the various methods and techniques that have been used in compliance measurements.

2.1 Definitions

There have been a number of different definitions used when referring to compliance. Qualitatively, it is simply a parameter used to describe how the pressure in a fluid will act to deform a material at the fluid boundary. It is a function of both material and geometric properties. Quantitatively, however, the definition is a bit more confusing. For example, if one refers to the modulus of elasticity, E, for a material, it is generally accepted that (given the proper assumptions) E is the slope of the stress-strain curve in the linearly elastic region for that material. It is always reported as having dimensions of force per unit area. In the case of compliance, there is no such accepted definition, nor is there any standard set of units.

Often, compliance will be expressed as per cent change in radius per unit change in pressure, i.e., mmHg^{-1} (Abbott, Megerman, Hasson, L'Italien and Warnock, 1987). A problem encountered is that a per cent change implies a change with re-

spect to some reference value. This reference can be taken at a variety of conditions. For instance, in this thesis, the reference point is different for different materials (see Chapter 4). In addition, many authors neglect to report this reference point making comparison of results difficult. Studies vary between the use of per cent change in radius, diameter, area and volume. Although these parameters are all related, it would be more convenient to have some standard for comparison. Some authors prefer to use the term 'volume distensibility' which is the percentage change in volume per mmHg rise in pressure. Empirically, it has been shown that in the human brachial artery, volume distensibility, d_V (or volume compliance), is related to the pulse wave velocity, $\underline{c}$, by

$$d_V = \left(\frac{3.57}{\underline{c}}\right)^2 \tag{2.1}$$

where $\underline{c}$ is in m/s (Gribbin, Pickering, and Sleight, 1979).

Another way compliance is sometimes expressed is in terms of wall stiffness, S.

$$S = \frac{\Delta p \times D}{\Delta D} \tag{2.2}$$

where p is the pulse pressure, D is the mid-diastolic internal diameter and ΔD is the change in diameter with each pulse (Christensen and Neubauer, 1985). Wall stiffness is inversely proportional to compliance and thus directly proportional to the modulus of elasticity (see Chapter 3).

A simple way to define compliance is as the slope of the volume-pressure curve during a slow infusion for a given tubular material. In other words,

$$C_V = \frac{dV}{dp} \tag{2.3}$$

where C_V is the volume compliance, V is the volume of the segment and p is the transmural pressure. If the segment is cylindrical in shape, then it can be assumed that the change in cross-sectional area is constant along the length of the segment. Then area compliance, C_A, can be expressed as $\frac{C_V}{l}$ where l is the segment length (see Chapter 3). The area compliance was the form of compliance used in this research.

2.2 Techniques

Measurement schemes can be categorized into two different types of techniques: (1) invasive or noninvasive techniques and (2) average or point measurements. Invasive and noninvasive obviously refers to using some host animal. Invasive implies invasion of the host (*i.e.*, breaking the skin) while noninvasive implies little or no intrusion into the host. Average measurements are those techniques used to obtain an average value of compliance over a length of vessel, while point measurements involve those techniques which obtain compliance at a point or single location along a vessel.

2.2.1 Average Measurements in Invasive Techniques

The traditional method of obtaining the compliance of an artery involves excising the vessel and mounting it into some type of infusion device. The vessel is infused with fluid, usually in a step-wise fashion, while recording the infused volume

and the pressure. An interesting phenomenon occurs if the transmural pressure is cycled over a range of pressures, *i.e.*, fluid is infused and then withdrawn from the lumen of the sample. The pressure-volume curve exhibits a hysteresis loop, therefore obtaining consistent values of compliance could be a problem if continuous repetitive testing is called for.

2.2.2 Point Measurements in Invasive Techniques

The classical approach here involves a sample holding device similar to the one in the previous technique, however, a cantilever transducer is used to record the change in external diameter rather than recording the infusion volume (Walden, L'Italien, Megerman, Abbott, 1980). The principal disadvantage in this method is the calibration of the cantilever transducer. Since it has rigid grips and the vessel wall is compliant, there will be some error introduced in the diameter measurement due to the rigid-compliant interface.

A variation on the traditional theme involves using an optical micrometer to track the changing external diameter of the segment rather than the infusion volume (Teodori, Rodgers, Brant, Borovetz, Webster, Steed, and Peitzman, 1986). There is a distinct advantage to this method, namely, that compliance can be plotted as a function of position *along* the length of the segment. This method lead to the discovery of the paraanastomotic hypercompliant zone, PHZ, that is always present on both sides of an arterial anastomosis. The PHZ refers to the area adjacent to the suture line where, due to a relatively rigid anastomosis, the local compliance increases. This results in a bulging effect causing increased stress at the anastomosis

as well as subintimal hyperplasia (SIH). It also causes increased impedance to flow, decreased distal perfusion and turbulence which could lead to graft thrombosis (Abbott, Megerman, Hasson, L'Italien and Warnock, 1987). This scheme also lends itself nicely to the study of compliance *in vitro* under dynamic conditions, *i.e.*, using a pulsating flow circuit to simulate *in vivo* conditions (Teodori, Rodgers, Brant, Borovetz, Webster, Steed, and Peitzman, 1986). It could even be used as an *in vivo* invasive technique although this would no doubt be difficult.

2.2.3 Average Measurements in Noninvasive Techniques

Examples of these techniques include the use of a mathematical model which utilizes parameters such as pressure and flow to obtain the 'lumped' compliance of a limb or section of the circulation. For instance, one model previously used by Levenson (Levenson, Simon, Maarek, Gitelman, Fiessinger, and Safar, 1985) is of the form

$$P = RQ_d - (RQ_d - P_0)e^{\frac{-t}{RC}} \tag{2.4}$$

where P is the pressure, R is the resistance, Q_d is the diastolic flow rate and C is the compliance. Flow and pressure can be obtained by any of the standard methods but resistance must usually be empirically determined or calculated, *i.e.*, mean arterial pressure divided by mean arterial flow. Even though this method may involve the use of a double-lumen catheter to track the pressure wave, it is still considered noninvasive because of the minimal risk and discomfort in introducing the catheter.

2.2.4 Point Measurements in Noninvasive Techniques

These techniques usually involve the use of ultrasound to record the change in the arterial diameter over the heart cycle. This can be accomplished quite accurately (although there is a high degree of variability) but the problem again becomes how to measure the corresponding pressure. Typically, a double-lumen catheter is used to track the pressure wave. Then compliance can be expressed as simply the percentage change in the geometric parameter, *i.e.*, radius or diameter, over the change in pressure (Laogun and Gosling, 1982).

3 DEVELOPMENT

As noted is Section 2.1, compliance can typically be expressed either on an area or a volume basis, and it is important to distinguish between the two. In general, volume compliance, C_V, is related to the increase in lumenal volume of a segment of artery resulting from a corresponding increase in transmural pressure. If the length of the segment is fixed, then the area compliance, C_A, is simply $\frac{C_V}{L}$ where L is the length of the segment. It is important to note, however, that determining C_A in this manner gives an average value since it is assumed that the cross-section is changing uniformly along the length of the segment. Given that compliance is a function of location in the arterial system, it is informative to use area compliance which can be directly compared to other segments in the arterial system as well as to similar segments in other subjects.

3.1 Steady Infusion Technique

Vessel area compliance, C_A, is defined as

$$\boxed{C_A = \frac{dA}{dp}} \tag{3.1}$$

where A is the lumenal area and p is the transmural pressure, although other defi-

nitions of compliance have been used (Christensen and Neubauer, 1985, and Nicolaides, 1985). Transmural pressure, p, is the difference between the internal and external pressure, $(p_i - p_e)$. If the external pressure equals atmospheric pressure $(p_e = 0)$, then $p = p_i$.

There have been a number of *in vitro* studies in which a segment of artery is excised and infused with fluid in a stepwise fashion. Each incremental volume increase causes some corresponding change in pressure. If the ends of the segment are fixed such that the length cannot change, and a relatively short segment is chosen such that taper can be neglected, then we can assume that the segment behaves as a cylinder with uniform cross-sectional area. The quantity $\frac{dA}{dp}$ is found by plotting change in A *vs.* p and thus C_A is simply the slope of this curve. One potential problem encountered when using a stepwise technique is that if there is a significant delay between each step, stress-relaxation can occur in the arterial wall. This can cause a decrease in pressure resulting in an artificially high value of compliance. To eliminate this problem in the present study, a slow, steady infusion was applied to the sample, and change in volume and pressure were recorded continuously throughout the test.

3.2 Dynamic Infusion Technique

A second technique of determining compliance is the dynamic infusion technique. For a compliant vessel closed at one end, such that there is no net flow,

$$dV = Qdt \tag{3.2}$$

where dV is the change in volume of the segment in a time dt, and Q is the volumetric flow rate. Dividing both sides by dp gives

$$\frac{dV}{dp} = \frac{Qdt}{dp} \tag{3.3}$$

where p is the transmural pressure. Dividing both sides by L and rearranging yields

$$\frac{dA}{dp} = \frac{Q}{L\frac{dp}{dt}} \tag{3.4}$$

or

$$\boxed{C_A = \frac{Q}{L\frac{dp}{dt}}} \tag{3.5}$$

Equation (3.5) is the fundamental equation of the dynamic infusion technique. Notice that C_A is simply a function of flow and pressure for a fixed segment length. This means that it is no longer necessary to measure small changes in the diameter of the vessel, but rather to record the pressure and flow waveforms simultaneously at one point.

3.3 Other Parameters

From C_A, two other useful parameters may be estimated using theoretical relationships. Since the stress-strain relationship for an artery is not linear, E is not constant (Dobrin, 1984b and Taylor and Santiago, 1986). However, we can define an incremental modulus, E_{inc}, whose value is determined over a small change in pressure. It can be shown that an approximate equation for E_{inc} is

$$E_{inc} = \frac{2\pi r_0^3}{C_A h_0} \tag{3.6}$$

where r_0 and h_0 are the radius and wall thickness of the segment at a given pressure, respectively. A second parameter, the pulse wave velocity, $\underline{c}$, can be estimated using the Moens-Korteweg equation

$$\underline{c} = \sqrt{\frac{E_{inc} h_0}{\rho d_0}} \tag{3.7}$$

where ρ is the density of the fluid and d_0 is the diameter of the segment. Both the incremental modulus of elasticity and the pulse wave velocity are important parameters which are used to describe not only the properties of the arterial wall, but also how the wall properties affect the flow of the blood through them. It has been shown that subjects with high blood pressure have higher pulse wave velocity values and hence less distensible (less compliant) arteries (Gribbin, Pickering, and Sleight, 1979).

4 MATERIALS AND METHODS

Two different materials were used in this research. The principal material used during the design and testing phases was latex rubber in the form of Davol™ Penrose drain tubing having a nominal diameter of about 6 mm. The length was variable but it usually was about 80 mm. The second material was a segment of canine carotid artery. The artery was only used after the automated testing process was perfected using the latex. After the process was perfected, three sets of data were collected using the same piece of latex to test the system for reproducibility. Then four dogs were sacrificed in order to determine if this method would provide a useful *in vitro* method.

4.1 Experimental Apparatus

A Plexiglas™ sample holder was designed to hold an arterial segment at a fixed length such that the sample could be mounted and then connected to the rest of the apparatus. The sample holder contains a fluid bath so that arterial samples can be bathed periodically in Tyrodes solution (see Appendix A). A series of pairs of Plexiglas™ plugs was fabricated having various outer diameters ranging from 2.5–5 mm with a groove so that the sample can be securely tied (see Figure 4.1). The plugs were designed to fit closely into the lumen of the segment such that the only

compliant part of the system is that section of artery actually being tested. Special sized plugs were made for the latex tubing such that the inner diameter of the latex matched the outer diameter of the plug for a snug fit. Each plug fits into the holder in the same fashion (see Figure 4.2). The sample holder has a removable plug holder at one end that fits into a series of slots on the bottom of the fluid bath. By changing the slot position, rough length adjustments can be made. Fine length adjustment can be achieved by sliding the plugs in the plug holder and then securing them into position with locking screws. In this way, a range of segment lengths between about 2–18 cm and diameters between 2.5–6 mm can be accurately mounted and tested. By selecting a plug size close to but not exceeding the inner diameter of the sample, the part of the sample used to secure to the plug will not affect the area being tested thus there will be little error due to end effects. Through choosing the appropriate plug size and accurately fixing the sample length, it is possible to test samples having a wide range of dimensions.

4.2 Arterial Segments

When arterial segments were tested, sections of canine carotid artery were harvested from mongrel dogs weighing 23-34 kg. The dogs were euthanized using SleepAway, 45 $\frac{mg}{kg}$ IV in the usual manner. Immediately following euthanization, the left common carotid artery was located and a section approximately 10 cm long was isolated. Figure 4.2 shows the approximate level where the section was isolated with respect to the major anatomical landmarks. A piece of white umbilical tape, previously marked in 1-cm increments was laid adjacent to the artery to

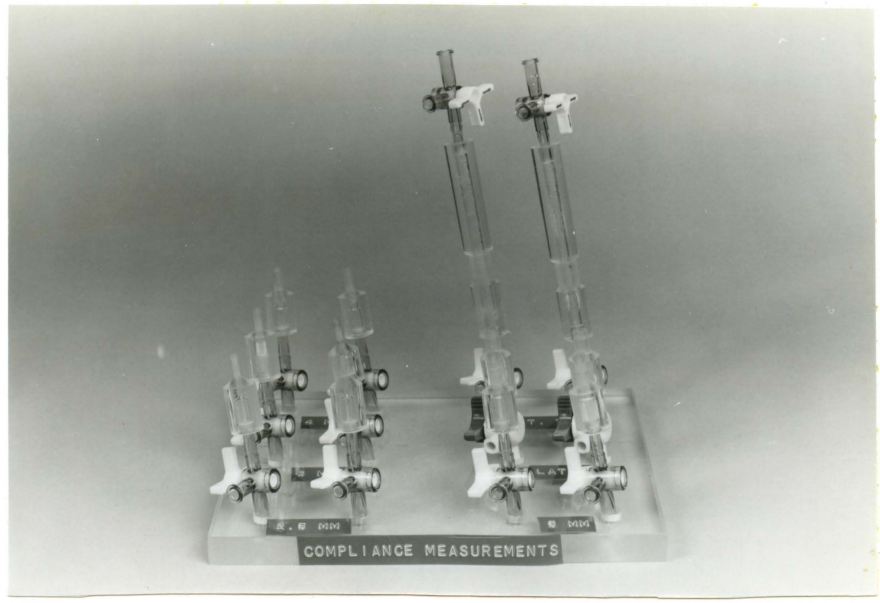

Figure 4.1: Photo of Plexiglas™ plugs designed to fit into the lumen of the sample. Notice the various diameters of the lumenal ends (pointing upward) to ensure a close fit for a large range of samples

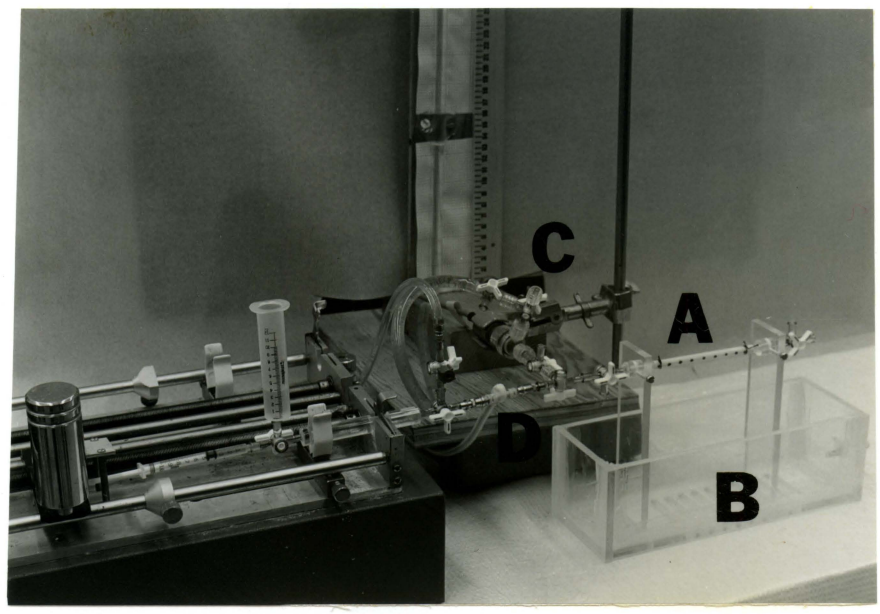

Figure 4.2: Photo of experimental setup including: A. Test Specimen, B. Specimen Holder, C. Pressure Transducer, D. Flow Probe

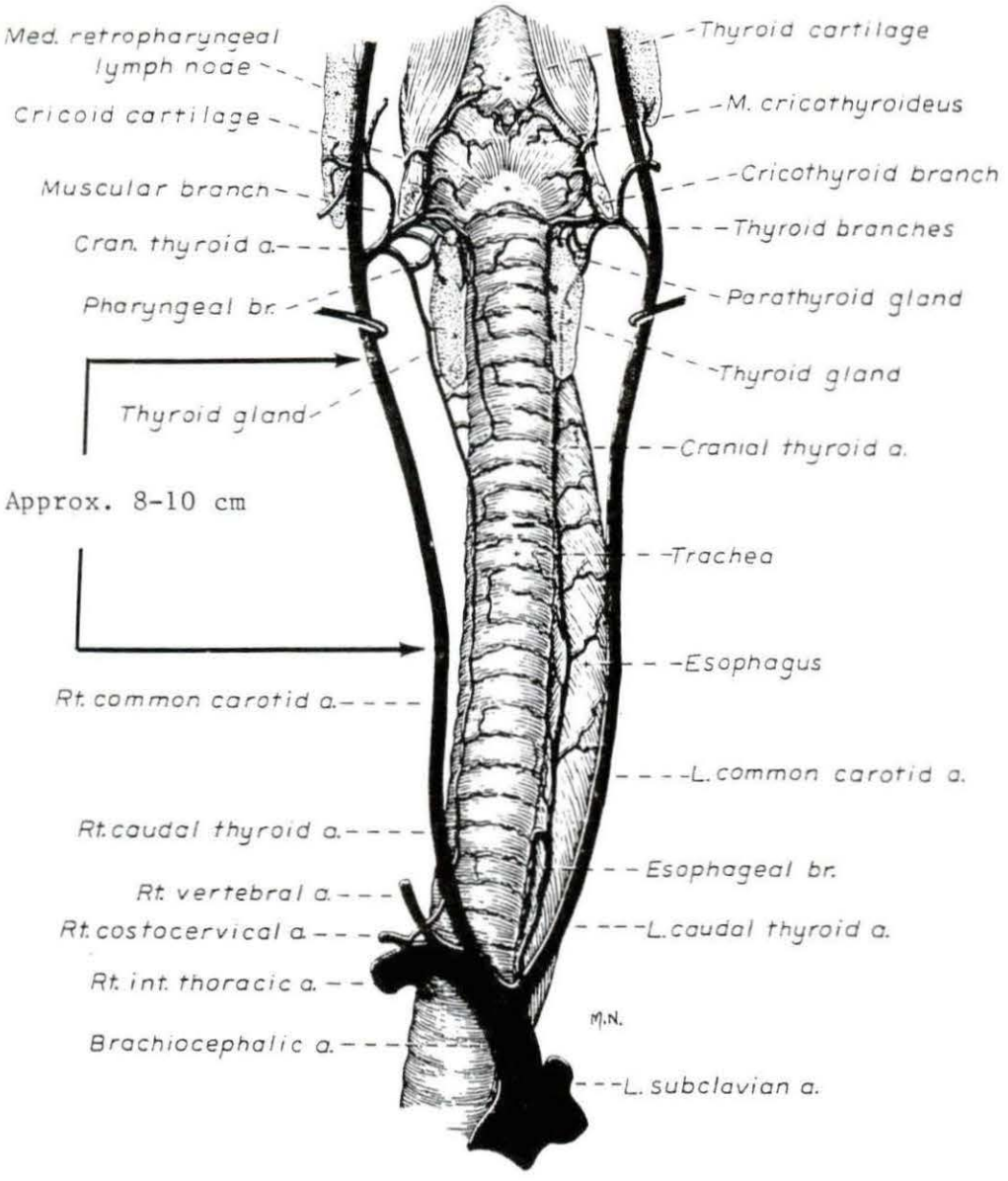

Figure 4.3: Anatomy of aortic arch in the canine neck. Arrows denote the approximate level at which the carotid arterial segments were obtained (Miller, 1968).

obtain an exact length. A series of ink dots were placed on the artery in 1-cm increments in order to stretch the artery to its original *in situ* length after excision and to insure the segment did not become twisted in the holder. Immediately upon excision, the segment was placed in refrigerated Tyrodes solution. A second section a few centimeters long was then removed proximal to the first section to be used for wall thickness measurements. Care was taken to minimize trauma to the arterial sections during removal; only minimal connective tissue and adventitia were removed to ensure a clean segment. The short section was ligated at one end, infused with a 3% glutaraldehyde solution to an internal pressure of approximately 100 mmHg, ligated at the other end, and placed in a beaker containing additional glutaraldehyde to fix the artery with a diameter and wall thickness close to the normal *in vivo* state. Approximately 90 minutes later, the artery was sectioned and put under an optical microscope to measure the wall thickness and reference diameter. Measurements were made at $0°, 90°, 180°$ and $270°$ around the cross-section and averaged. The original section was mounted in the sample holder and flushed with Tyrodes solution (pH=7.4) at 37°C. Testing began within 30 minutes of euthanization. The pressure was increased to 100 mmHg and held there while a suture was wrapped around the outside of the artery 4 times and tied. Then the suture was cut and the length was measured to determine the outer diameter. The inner diameter was calculated by subtracting twice the wall thickness from the outer diameter ($d_o - 2h_0$). The arterial wall is virtually incompressible so h_0 can be treated as a constant (Doyle and Dobrin, 1971). Typical dimensions for one latex tube and one canine carotid artery (Dog #2) are given in Table 4.1. Similar data

Table 4.1: Typical measured physical parameters comparing latex and arterial samples

	Latex	Artery	Range for Artery[a]
Length, cm	8.32	7.48	—
Outer Diameter, cm	0.612	0.548	—
Wall Thickness, mm	0.356	0.401	0.2 - 0.4
Inner Diameter, cm	0.576	0.508	0.2 - 0.8
$\frac{h}{d_i}$ Ratio	0.062	0.079	0.053 - 0.095

[a] Reported range for canine carotid arteries (see Caro *et al.*, 1974)

for the remaining latex and arterial segments can be found in Appendix B.

4.3 Hardware

In an attempt to design an automated system capable of running both the steady and dynamic tests, an IBM PC/AT computer was used in combination with a Keithley data acquisition system. Other hardware used in this research included the following: Harvard Apparatus Dual Infusion/Withdrawal Pump Model 945, Harvard Apparatus Pulsatile Blood Pump Model 1421, Biotronex Laboratory Pulsed Logic Electromagnetic Flowmeter Model BL-610, Grass Model 7 Polygraph, Gould-Statham Physiological Pressure Transducer Model P23Db and an In Vivo Metric Flow Probe (see Figure 4.2). During the steady infusion test, pressure and change in volume were sampled at a frequency of 2 Hz for 150–180 seconds. In the dynamic infusion test, the sampling frequency for the flow and pressure waves was 64 Hz.

Approximately 15 wave cycles were collected; pulsations were generated at 57 beats per minute. The pressure and flow waveforms were digitally filtered using standard low-pass moving average filters; the steady infusion data required no filtering. A series of custom programs were written in Basic, C and SAS (Statistical Analysis System) and were executed via batch files (see Chapter 5). The software was

responsible for running diagnostics to make sure the equipment was functioning properly, calibrating the pressure and flow transducers, turning on and off the infusion and pulsatile pumps, running both the steady and dynamic infusion tests and collecting, filtering, processing and displaying the data. After mounting the sample, the operator merely types 'COLLECT' and follows the instructions prompted by the computer. It takes about half an hour to go through the whole procedure to test one sample.

5 SOFTWARE

The collection of data during this research was accomplished by using an IBM PC/AT computer and a Keithley Data Acquisition System. Most of the software used was specifically written for this project in an attempt to make the data collection and processing as completely automated as possible.

The process is broken up in sections that are controlled via batch files. A batch file is a set of instructions that tell the computer in what order to execute a series of programs or other specified tasks. A *master* batch file, called COLLECT is the file that regulates a cascade of programs and other batch files in the execution of both the steady and dynamic infusion methods. The following sections will describe the events and procedures in the order handled by COLLECT. Typing the word 'COLLECT' at the DOS prompt initiates the entire process. The source code for COLLECT can be found in Appendix C. Due to the complicated nature of the sequence of batch files and programs, a flow chart is included (Figure ??) indicating the sequence of major events.

5.1 Calibrat

The first thing that happens after typing COLLECT is that another batch file called CALIBRAT is executed. CALIBRAT is responsible for running the diagnos-

tic programs on the equipment before any data are collected and then calibrating both the pressure and flow probe transducers. Since there is a considerable amount of hardware under computer control, it is critical that all of the equipment be functioning properly and reliably before the computer takes full control of the experiment. The source code for CALIBRAT and the corresponding programs can be found in Appendix D.

5.1.1 Diagnostics

CALIBRAT starts by executing two BASIC programs, called TESTSWIT and VOLTCHK.

5.1.1.1 Testswit TESTSWIT.BAS tests the operation of the mechanical relay switch that controls the power to the infusion pumps. The operator is prompted to toggle the pumps on and off several times via the keyboard. This test is necessary because the relay contains a 9-volt battery and with repeated use the battery will no longer have the potential necessary to open and close the relay properly. Also, it makes sure that the power is on to both pumps and that they are working properly.

5.1.1.2 Voltchk VOLTCHK.BAS is a diagnostic program used to insure that the voltage signals going into the A/D converter are the same as the voltages being reported by the PC to be used by the other software. If these voltages are not the same, the validity of all the data collected hereafter would be questionable. A continuous voltage signal is displayed to the screen and the operator is prompted to

verify that the voltage displayed equals the voltage reported by a digital volt meter connected in parallel to the Grass recorder. If necessary, a DC voltage generator can be connected directly to the Keithley as a further diagnostic procedure.

Both of the above programs are very short and will ensure the proper and accurate operation of the process software.

5.1.2 Calibrations

Following the diagnostics, CALIBRAT starts the calibration of the pressure and flow probe transducers. It is interesting to note that these calibration routines were written in a general enough fashion to facilitate there use in any research where repetitive calibrations are required. Once the equipment is set up properly, it is a simple procedure to calibrate the transducers and get the voltage-pressure or voltage-flow relationships.

5.1.2.1 Prescal To calibrate the pressure transducer, a BASIC program called PRESCAL.BAS is run. The operator inputs the name of the data file to store the calibration data and the transducer height into the computer. Then the operator reads the height of the column of water in a piezometer tube and enters the value into the computer. The computer takes 100 digital samples, averages them, and converts the result to a voltage. The computer also calculates the standard deviation of the samples. The standard deviation is used as a measure of instability in the system. If the standard deviation is greater than 0.1, then the calibration point is remeasured and the suspect value is neglected. A message is sent to the operator to check the system for leaks, bad connections, etc., which could cause

such a problem to be detected. The operator opens one valve to drain some fluid out of the manometer and then takes another reading. After each calibration point, the following information is displayed to the screen:

(1) actual pressure head in cm H_2O
(2) corresponding pressure in mmHg
(3) voltage in volts
(4) standard deviation
(5) total number of points collected thus far.

After at least 10 calibration points are collected, the computer will display all the calibration data collected thus far and prompt the user to either save the data to a disk or redo the calibration procedure again. After the data are saved, it can be recalled to the screen to verify storage. At this point, the computer asks the user if it is necessary to enter the DOS environment for file manipulation, etc. Finally, at the conclusion of the pressure transducer calibration, PRESCAL.BAS returns control to CALIBRAT to execute the next program called PRESCAL.SAS.

PRESCAL.SAS is a short SAS program which does a linear regression on the pressure calibration data to determine the conversion parameters necessary to convert the voltage signal into the corresponding pressure signal. The complete statistical analysis of each point is automatically outputted as hard copy to the printer. In addition, a correlation coefficient is calculated; this value must be 0.99 or better for the calibration to be valid. Also, PRESCAL.SAS generates a plot of pressure vs. voltage to the screen so that the calibration curve can be visually inspected. Control is again returned to CALIBRAT.

5.1.2.2 Flowcal Upon completion of the pressure transducer calibration, CALIBRAT initiates the calibration of the flow probe transducer. This is accomplished via a BASIC program called FLOWCAL.BAS. The logic of FLOWCAL.BAS is basically the same as PRESCAL.BAS: the operator inputs a data file name (the default name is always displayed), makes a series of data points (at least 10) and stores the data to a disk. A screw clamp is placed on the supply tubing so that the flow rate through the flow probe can be finely controlled. The flow is directed into a graduated cylinder to be collected. The computer prompts the operator to tap 'C' when a constant flow is achieved and the water level in the graduated cylinder is at a convenient level. At this point, the computer samples the flow signal at 8 Hz for about 15 seconds and displays the data on the screen (note that only the elapsed time is critical here and not the sampling frequency). After the designated time, a tone is sounded and the flow is stopped. The operator enters the volume of fluid collected and the computer displays the following data:

(1) total number of points collected thus far
(2) average voltage in volts
(3) actual volume infused in mm^3
(4) actual elapsed time in seconds (s)
(5) volumetric flow rate in mm^3/s.

When a sufficient number of calibration points are collected, a summary of the data are displayed to the screen, the data are stored and control returns to CALIBRAT.

FLOWCAL.SAS is another short SAS routine which does a linear regression on the flow probe calibration data to determine the conversion parameters necessary to convert the voltage signal into the corresponding flow signal. As in PRESCAL.SAS,

the complete statistical analysis of each point is automatically outputted as hard copy to the printer including the correlation coefficient; this value must be 0.99 or better for the calibration to be valid. Also, FLOWCAL.SAS generates a plot of pressure vs. voltage to the screen so that the calibration curve can be visually inspected. Control is returned to CALIBRAT which completes the calibration process. At this point, control recedes back to COLLECT for the initiation of the steady infusion testing.

5.2 Steady

The next batch file in the COLLECT list is STEADY. STEADY is responsible for execution of the steady infusion testing. The source code for STEADY and the corresponding programs can be found in Appendix E.

5.2.1 Compli

STEADY begins by executing a BASIC program called COMPLI.BAS which controls the actual collection of the steady infusion data. Upon its execution, COMPLI.BAS prompts the operator to enter the calibration results that were previously printed by PRESCAL.SAS. Also, it is necessary to enter the physical parameters of the system such as piston velocity of infusion pump (cm/s), distance piston is to be traversed (cm), the length of the vessel segment that can actually undergo expansion (cm) and the internal diameter of the vessel (cm). Since it is assumed that these initial parameters do not change during the testing of each individual segment, they can be entered once and be used again and again for repetitive tests,

or they can be changed by the operator between tests if the vessel is changed. Then, via the digital output channel of the Keithley and a mechanical relay switch, the infusion pump is toggled via the IBM keyboard. The pump is positioned such that it just starts to move the syringe plunger and the pressure in the system starts to increase very slightly. Up to this point, the operator is in control. Now, by the touch of one key, the computer takes full control. The pump is turned on and the pressure and cross-sectional area are recorded at a sampling frequency of approximately 2 Hz for an infusion duration of 3-5 minutes.

The pressure is measured directly by the pressure transducer. The cross-sectional area is measured indirectly by knowing two parameters: (1) the velocity of syringe plunger (which is the same as the velocity of the infusion pump), and (2) the relationship between the linear displacement of the syringe plunger and the corresponding volume of fluid ejected from the syringe. For a 1 cc syringe, a 5.842 cm linear displacement yields 1 cc of fluid ejected. Thus,

$$A - A_0 = \frac{v\Delta t}{5.842 * l * 100} \tag{5.1}$$

where $A - A_0$ is the average change in cross-sectional area of the vessel (mm^2), v is the velocity of the infusion pump piston (cm/s), Δt is the elapsed time of the infusion (s) and l is the length of the compliant region of the vessel (cm). During the actual data collection, the screen displays the time remaining for that trial and the pump status (on or off). The actual code for this section of the experiment is shown below.

```
700 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

```
710 'PRESSURE (VOLTAGE) AND VOLUME MEASUREMENT
720 CLS
730 POKE 8,0
740 DEF SEG = &HCFF8
750 LOCATE 10,10:PRINT "PUMP IS ON - PRESSURE AND VOLUME ARE
       BEING RECORDED."
760 J=0:E=0
770 T=TIMER                                  'start time
780 POKE 8,1                                 'pump on
790 WHILE VELx(TIMER-T)<DIST
800     E=E+1
810     IF E>10 THEN 820 ELSE 850
820          LOCATE 13,10
830          PRINT USING "TIME REMAINING = ####.#
                 SECS.";(DIST/VEL)-(TIMER-T)
840          E=0
850     J=J+1                        'j=total number of samples
860     POKE 1,6:POKE 26,0:POKE 10,0:POKE 24,0
870     D(J)=(256x(PEEK(3)-240)+PEEK(2)-2047)x20/4096
                                             'd(j) in volts
880     X(J)=VELx(TIMER-T)/5.842/LENGTHx100     'x(j)=A-Ao,
                                 sqmm (1cc=5.842cm)
890     F=TIMER
900     IF (TIMER-F)<.2 THEN 900             'sampling rate=2Hz
910 WEND
920 POKE 8,0                                 'pump off
930 TT=TIMER                                 'stop time
940 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

At the end of the infusion, the pump is turned off and the pressure is digitally filtered with a low-pass 5-point moving average filter. Then, using the parameters entered at the beginning of the program, the voltage values are converted into pressure and a second area characteristic, that of $\frac{A-A_0}{A_{ref}}$ as a per cent increase in area, is calculated. A_{ref} refers to the reference area for that particular material (see Chapter 6). Summary information for the particular trial is displayed to the screen

including:

(1) duration of infusion (s)
(2) distance traversed by piston (cm)
(3) volume of fluid infused (cm^3)
(4) per cent increase in segment volume
(5) total number of *filtered* points
(6) length of the segment (cm)

This information is also outputted to the printer for a written summary. The data are stored in a data file to a disk and the operator is asked if it is necessary to enter DOS for file manipulation, etc. COMPLI.BAS concludes by returning control to STEADY.

COMPLI.SAS is a SAS routine that STEADY executes following COMPLI.BAS which will display a plot of $A - A_0$ and $\frac{A-A_0}{A_{ref}}$ *vs.* pressure and will fit a curve to the data of the form

$$A - A_0 = c_1 p^2 + c_2 p + c_3 \tag{5.2}$$

where c_1, c_2, and c_3 are the curve coefficients. COMPLI.SAS takes the derivative of the above equation, $\frac{d(A-A_0)}{dp}$ and generates a second plot of C_A *vs.* p which will be linear of the form

$$C_A = 2c_1 p + c_2 \tag{5.3}$$

where C_A is the average area compliance of the vessel. The statistical analysis, including the coefficients of the above equations is output to the printer and control is again returned to STEADY.

5.2.2 Calc

The final program to be executed by STEADY is a BASIC program called CALC.BAS. CALC.BAS is a supplemental program in that it is not directly involved in the testing progress. It is a *stand-alone* program that is used to convert the results of COMPLI.SAS into useful information. CALC.BAS will calculate the values of compliance, incremental modulus of elasticity and pulse wave velocity from Equations (3.1), (3.6) and (3.7). The operator simply inputs the curve constants generated by COMPLI.SAS and the computer will output equations for the change in area, $A - A_0$ and compliance, C_A as a function of pressure, p. Then the operator inputs the pressure range to consider, Δp, the reference diameter, d_{ref}, the wall thickness, t, and the density of the fluid, ρ, and the computer will calculate C_A, E_{inc} and $\underline{c}$ in the given pressure range.

5.3 Dynamic

COLLECT next calls up a batch file named DYNAMIC. DYNAMIC is responsible for running the dynamic infusion testing. The source code for DYNAMIC and the corresponding programs can be found in Appendix F.

5.3.1 View

DYNAMIC starts by executing VIEW.BAS. VIEW.BAS is the BASIC program that collects the pressure and flow waveform data and displays the waves on the screen. Several sets of data can be collected and saved under different file names for retrieval at a later time. Upon its execution, VIEW.BAS prompts the operator to

enter the calibration data for both the pressure and flow probe transducers obtained in CALIBRAT and the compliant length of the vessel. Next the pulsatile flow pump is turned on, and after a few seconds delay to eliminate transient effects, both the pressure and flow wave channels are sampled at 64 Hz and simultaneously displayed to the screen. The actual code used to sample the pressure and flow waves is shown below:

```
620 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
630 'CHANNEL 0 (PRESSURE) DATA COLLECTION
640 POKE 10,0          'channel selection = 0  (pressure)
650 POKE 24,0
660 P(J)=(256x(PEEK(3)-240)+PEEK(2)-2047)x20/4096 'p(j) in volts
670 PSET(N,A-P(J)xY)
680 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
690 'CHANNEL 1 (FLOW) DATA COLLECTION
700 POKE 10,1           'channel selection = 1 (flow)
710 POKE 24,0
720 Q(J)=(256x(PEEK(3)-240)+PEEK(2)-2047)x20/4096 'q(j) in volts
730 PSET(N,B-Q(J)xZ)
740 J=J+1
750 NEXT
760 TOTALT=TIMER-T
770 INCT=TOTALT/N
780 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

Notice that there are a minimum number of operations between the two actual sampling operations (lines 660 and 720). All unit conversions and filtering is done after completion of data collection. This is done to minimize any phase shift that may occur between waves, although there will always be some small inherent shift. In most applications, this is not critical. However, for any time, t, $p(t)$ and $Q(t)$ will

be used in the same division operation and a phase shift will introduce an additional distortion into the results.

After the data are collected, the waves can be displayed to the screen for visual inspection. If the data are suitable, the operator instructs the computer to convert the voltages to pressures and flows and then store the data to a disk. Filtering is accomplished in the sequential program because the filters may be altered to achieve best results.

5.3.2 Dyncomp

DYNCOMP.BAS is a BASIC program that does a number of operations to the data obtained previously in VIEW.BAS. It inputs the wave data (from any appropriate file) and preforms a low-pass filtering operation on the data via a 3-point moving average filter on the pressure wave and a 7-point moving average filter on the flow wave. Then it selects a small section of data, approximately 2 or 3 wave cycles, and stores it to a disk. These are the actual waveforms used for the compliance calculation. It then finds the maximum and minimum pressures that occur in the chosen region of data and asks the operator to enter the percentage of the pressure wave to be *clipped* from the top and bottom of the wave. This is done to avoid the undefined regions generated by Equation 3.5. To include the undefined regions, the operator enters 0%. The program then proceeds to calculate the slope of the pressure wave, $\frac{dp}{dt}$, and the dynamic volume compliance, C_V. The code for these operations is shown below:

```
940 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

```
950 'CALCULATION OF DYNAMIC VOLUME COMPLIANCE
960 LOCATE 8,10
970 BEEP
980 INPUT "Enter amplitude of PRESSURE wave to be neglected
        (i.e., 5%=5)";A
990 A=A/100
1000 CLS
1010 LOCATE 10,12
1020 PRINT "Now calculating DYNAMIC VOLUME COMPLIANCE, please
         wait..."
1030 D=1
1040 FOR B=1 TO C-1
1050 IF PRES(B)<(1+A)xPMIN OR PRES(B)>(1-A)xPMAX THEN 1210
1060       AVGQ=0:DPF=0:DPB=0:DTF=0:DTB=0:DPDTF=0:DPDTB=0:DPDT1=0:
               TEMP=0
1070       AVGQ=(FLOW(B-1)+FLOW(B)+FLOW(B+1))/3
1080       DPF=PRES(B+1)-PRES(B)
1090       DPB=PRES(B)-PRES(B-1)
1100       DTF=TIME(B+1)-TIME(B)
1110       DTB=TIME(B)-TIME(B-1)
1120       DPDTF=DPF/DTF
1130       DPDTB=DPB/DTB
1140       DPDT1=(DPDTF+DPDTB)/2
1150       IF DPDT1=0 THEN LOCATE 12,15:PRINT "DPDT1=0. Point
               skipped.":GOTO 1210
1160       TEMP=AVGQ/DPDT1/LENGTH/133.3/10^6x10^10  'm4/N (10)-10
1170       IF TEMP<-20 OR TEMP>20 THEN 1200
1180       DPDT(D)=DPDT1
1190       COMPLI(D)=TEMP
1200       D=D+1
1210 NEXT
1220 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

Notice that for each point, the program loops between lines 1040 and 1210 calculating a number temporary parameters. Line 1050 excludes those points to be neglected (if appropriate). Note from Equation 3.5 that we need the flow wave

divided by the *slope* of the pressure wave. Thus, we need a method of digitally obtaining $\frac{dp}{dt}$. Since the pressure wave typically has a very high *signal-to-noise* ratio and the low-pass filter will smooth the data even more, then we can use the fairly simple Gregory-Newton interpolation formula to evaluate $\frac{dp}{dt}$ (Wylie, 1961). In this method, three adjacent points, say p_1, p_2 and p_3, are used to calculate an average slope. The slope from 1 to 2 and 2 to 3 (DPDTF and DPDTB in lines 1120 and 1130, respectively) are calculated and then the two are averaged (DPDT1 in line 1140). Line 1150 makes sure the *net* slope is not zero (causing a division by zero in Equation 3.5. Line 1160 calculates the compliance (TEMP) in $m^4/N \times(10)^{-10}$. One last check is preformed to make sure the compliance is within the specified range (for plotting purposes) and finally, $\frac{dp}{dt}$ and C_A are stored in there respective arrays in lines 1180 and 1190. This results in two waves, $\frac{dp}{dt}$ and C_A as a function of position on the wave cycle. Control is again returned to DYNAMIC.

Next, VIEW.SAS is run which plots the pressure and flow waves to the screen and then DYNCOMP.SAS plots $\frac{dp}{dt}$ and C_A *vs.* time on the wave cycle. This concludes the DYNAMIC batch file and control reverts back to COLLECT at this point.

5.4 Cleansas

Finally, the batch file called CLEANSAS removes any temporary files that may have been written to the hard drive during this procedure. Notice that at this point, there are three cascading batch files running simultaneously. The source code for CLEANSAS can be found in Appendix G.

6 RESULTS

6.1 Steady Infusion Technique

With this technique, an infusion pump is used to maintain a small constant flow of saline into the compliant vessel. By knowing the velocity of the pump piston, the duration of the infusion and the relationship between the linear displacement of the syringe piston and the volume displaced, the volume of fluid infused, $\Delta V(t)$, and the pressure, $p(t)$, were continuously recorded. Dividing $\Delta V(t)$ by L gives $\Delta A(t)$ which is the change in cross-sectional area. Since $\Delta A(t) = A - A_0$, where A is the average area at a time, t, and A_0 is the original area, $\frac{\Delta A}{A_{ref}} \times 100$ is the percent increase in cross-sectional area with respect to a reference area. Note that A_{ref} is the area at a given pressure, p_{ref}. This reference pressure was not the same for the latex and arterial samples, because it was not possible to measure the diameters of the latex and the artery at the same pressures. Thus, A_{ref} (latex) was measured at $p = 0$ and A_{ref} (artery) was measured at $p = 100$ mmHg. Although the reference areas are different, values for C_A are unaffected by this difference because A_{ref} is not used in the compliance calculations. Table 6.1 shows the results of three steady infusion tests on the same piece of latex. The segment was removed from the sample holder and then replaced between each trial to test for reproducibility. Note that

although there is some variation in the curve coefficients, c_1, c_2 and c_3, there is very little variation in the compliance, incremental modulus of elasticity and pulse wave velocity values.

After testing the latex segments, four dogs were euthanized to obtain carotid artery samples (see Appendix B). Since Dog #1 was the first arterial sample to be tested, it was necessary to carry out the tests several times to eliminate any bugs that still existed in the hardware and software. Due to excessive testing, the sample was exposed to undo trauma over a prolonged length of time and thus reliable compliance data could not be determined. After mounting the segment from Dog #3, it was found that there was some fluid leakage from the segment during the tests. Although no visible holes in the segment were found, the compliance could not be determined due to a leaky vessel wall. Testing on segments from dogs #2 and #4 were accomplished with no major problems.

Figure 6.1 shows a plot of the percent change in area *vs.* pressure for the latex and arterial samples. Notice that for latex, the curve is slightly concave upward while for artery, the curve is concave downward. This is due to the fact that the artery does not act as a merely passive sample; as the pressure increases, the artery becomes stiffer thus reducing the compliance. This is seen in Figure 6.3 which shows C_A *vs.* p based on the data from Figure 6.1. Notice also that for low pressures, the compliance of the artery is greater than for the latex, but as the pressure increases, the difference becomes smaller until at $p = 172$ mmHg, the compliance of the two materials become equal. Some typical values for C_A, E_{inc} and $\underline{c}$ are given in Table 6.2 for one latex and one canine carotid artery segment obtained from the steady

Table 6.1: Results of steady infusion method for latex sample

Trial	c_1 $\times 10^{-5}$	c_2 $\times 10^{-2}$	c_3 $\times 10^{-2}$	$A - A_0$, mm^2, at $p = 100$ mmHg	C_A $m^4/N \times 10^{-10}$, at $p = 100$ mmHg	E_{inc}, MPa, at $p = 20$ mmHg	Pulse Wave Velocity, c, m/s
1	2.17	1.41	-4.59	1.57	1.37	3.84	15.3
2	1.90	1.46	3.87	1.69	1.38	3.74	15.1
3	1.85	1.47	4.13	1.69	1.38	3.71	15.0

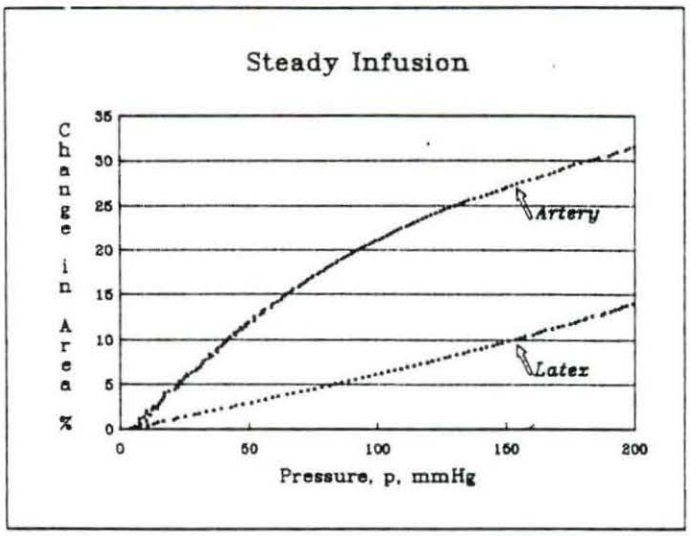

Figure 6.1: Change in area, $\frac{\Delta A}{A_{ref}}$, as a function of transmural pressure from the steady infusion technique for Dog #2

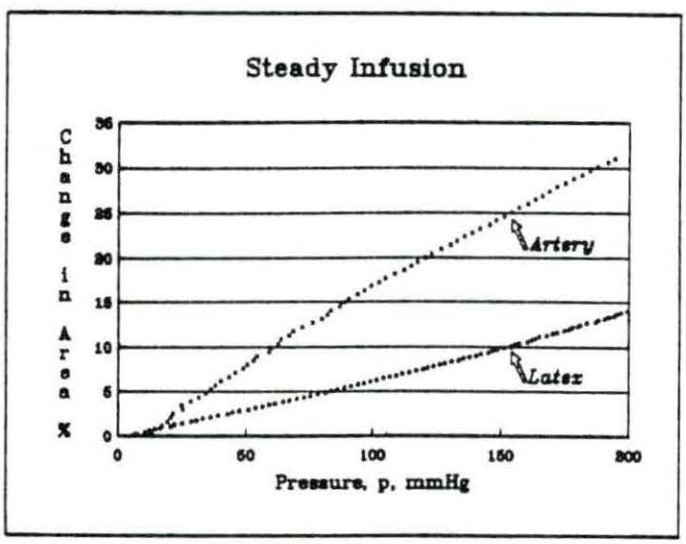

Figure 6.2: Change in area, $\frac{\Delta A}{A_{ref}}$, as a function of transmural pressure from the steady infusion technique for Dog #4

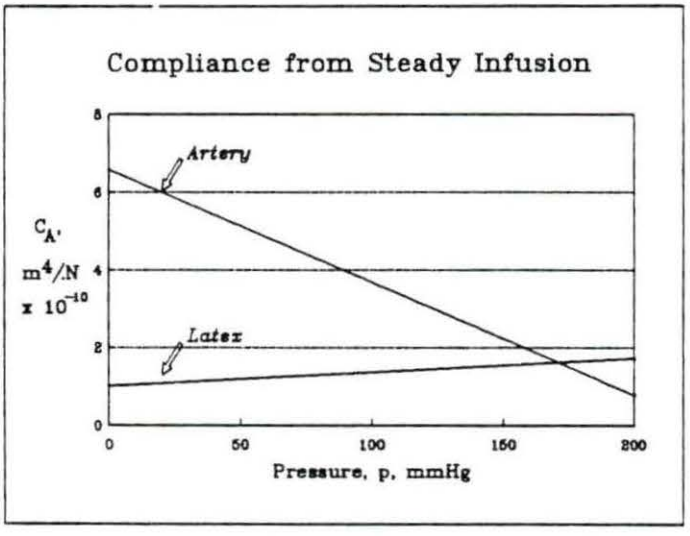

Figure 6.3: Area compliance as a function of transmural pressure from the steady infusion technique for Dog #2

infusion technique. The modulus of elasticity of the latex used in this research was not directly measured, so it was necessary to use reported values for comparisons. There are a number of variations of latex materials which will cause inconsistancies in mechanical properties. For instance, Monroe (1970) reports E_{inc} for latex at $p = 20$ mmHg to be 2.1 MPa while Papageorgiou (Papageorgiou and Jones, 1987) reports a value of 0.858 MPa for a $\frac{h}{d}$ value of 0.10 (the latex used in this research had a $\frac{h}{d}$ of 0.062). In fact, Papageorgiou reports that for latex at a $\frac{h}{d}$ of 0.2, $E = 1.50$ MPa which is nearly twice the value at a $\frac{h}{d}$ of 0.10 for the same material. In addition, in synthetic rubbers, E is a function of temperature, *i.e.*, for a given latex at $T = 20°$C, $E = 1.50$ MPa while at $T = 60°C$, $E = 1.05$ MPa (a 43% change over a 40°C temperature range).

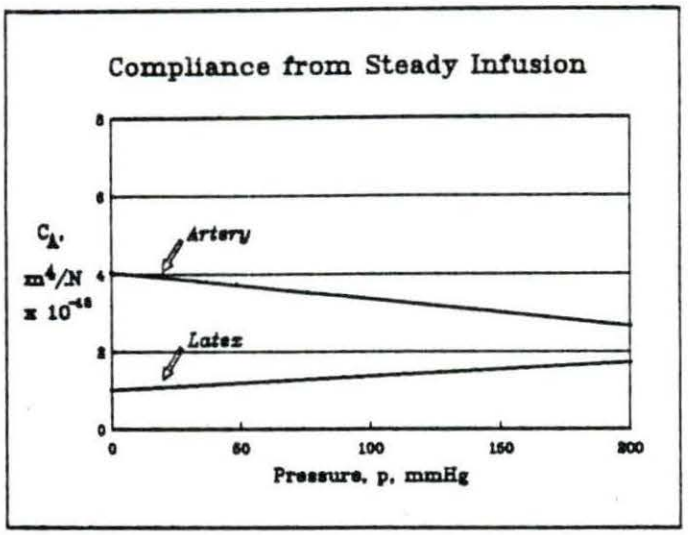

Figure 6.4: Area compliance as a function of transmural pressure from the steady infusion technique for Dog #4

Table 6.2: Comparison of material properties of latex and arterial samples from the steady infusion technique. () denotes reported values

	Latex	Artery
Compliance, $\frac{m^4}{N} \times 10^{-10}$ at $p = 100$ mmHg	1.38	3.68 $(9.07)^a$
Incremental Modulus of Elasticity MPa at $p = 20$ mmHg	3.72 $(2.1)^b$	0.65 $(0.7 - 1.1)^c$
Pulse Wave Velocity, m/s	15.03 $(9.48)^b$	7.17 $(8 - 8.5)^c$

[a] See Dobrin (1984b).
[b] See Monroe (1970).
[c] See Caro (Caro, Pedley and Seed, 1974).

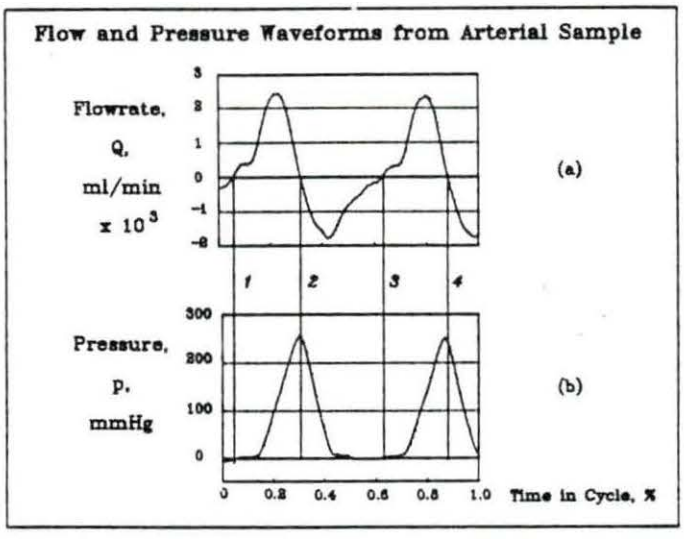

Figure 6.5: *In vitro* (a) flow and (b) pressure waveforms in the canine carotid artery

6.2 Dynamic Infusion Technique

With this technique, a pulsatile flow pump is used to simulate *in vivo* conditions. However, since the distal end of the vessel segment is occluded, there is no net flow. The time averaged flow rate must be equal to zero over a cycle indicating that the net forward flow into the segment must equal the net retrograde flow leaving the segment. Obviously, this is not the normal *in vivo* condition, however, it is analogous to occluding, for example, blood flow at the wrist and recording pressure and flow waveforms in the brachial artery near the elbow.

Figure 6.5 shows observed waveforms of flow and pressure in a canine carotid artery *in vitro*. We define the starting point of a cycle to be where the flow and pressure are both zero. This is line 1 in Figure 6.5. The end of the cycle is line 3.

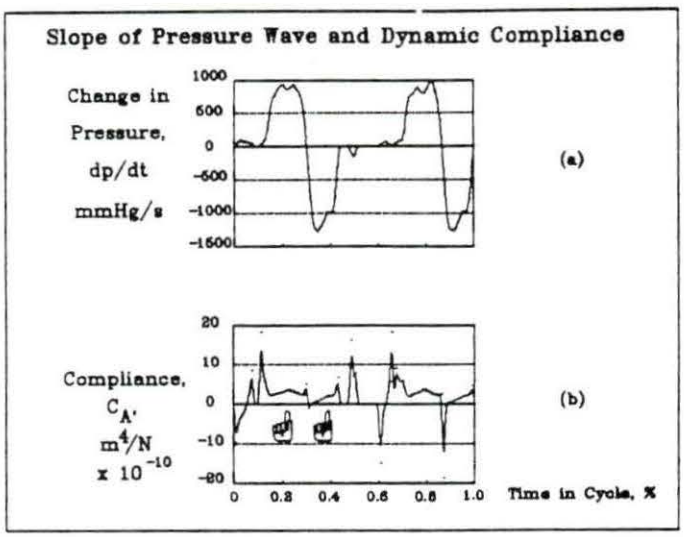

Figure 6.6: *In vitro* (a) slope of the pressure waveform in Figure 6.5b and (b) compliance using Equation 3.5 as a function of position on the wave cycle

At points where $Q = 0$, the pressure must be at either a maximum or a minimum and C_A is indeterminate (from Equation 3.5). This condition is shown by lines 1 through 4.

Figure 6.6a shows $\frac{dp}{dt}$, the slope of the pressure wave in Figure 6.5b and Figure 6.6b is the compliance obtained using Equation 3.5. The horizontal scale not only denotes time but can also be thought of as pressure since each time, t, corresponds to a specific pressure, $p(t)$ (from Figure 6.5b). Thus, Figure 6.6b shows compliance *vs.* pressure in a similar fashion as Figure 6.3. As noted, Equation 3.5 cannot be used when $\frac{dp}{dt} = 0$ (division by zero). The major spikes seen in Figure 6.6b are the result of the numerical analysis used to generate the plot. As seen in Figures 6.5b and 6.6a, $\frac{dp}{dt} = 0$ when the pressure is at a maximum or a minimum. These points

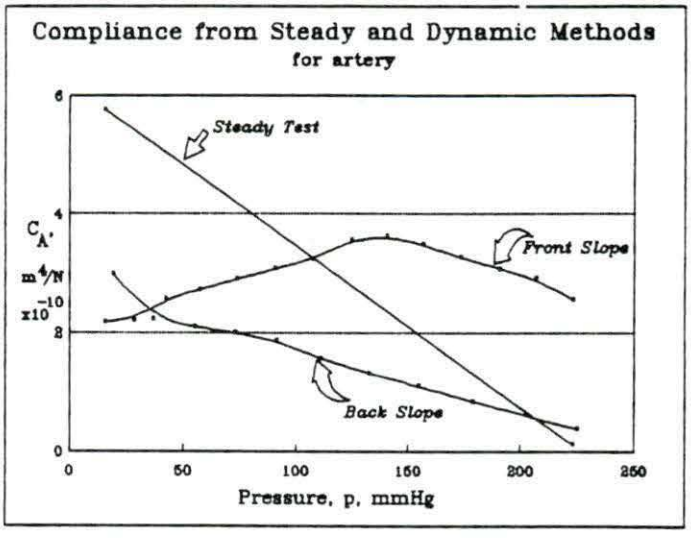

Figure 6.7: Comparison of compliance as a function of pressure from the steady and the dynamic infusion techniques on an *arterial segment* from Dog #2

can be thought of as identifying regions where Equation 3.5 is not valid, and these are the regions where spikes occur in Figure 6.6b. Between these regions, denoted by the pointers in Figure 6.6b, the compliance can be approximated. Recalling that Figure 6.6b is essentially a plot of C_A *vs.* p, and that every value of p occurs twice in each wave cycle, we can enlarge the marked regions in Figure 6.6b and compare them with the results of the infusion technique in Figure 6.3. This comparison is shown in Figure 6.7.

The left and right pointers in Figure 6.6b denote the front and back slopes of the pressure wave in Figure 6.5b, respectively. Figure 6.7 is a plot comparing the results of the steady and dynamic infusion techniques: the curves are drawn in to denote which set of points corresponds to which slope face. Figure 6.7 also shows

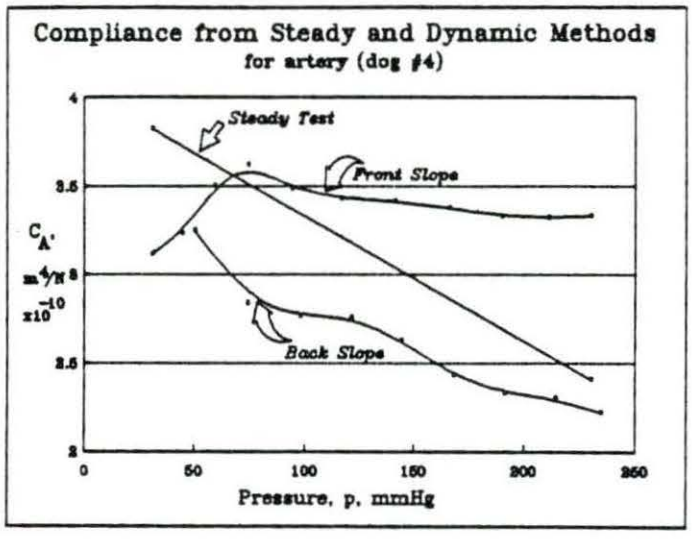

Figure 6.8: Comparison of compliance as a function of pressure from the steady (Figure 6.4) and the dynamic infusion techniques on an *arterial segment* from Dog #4

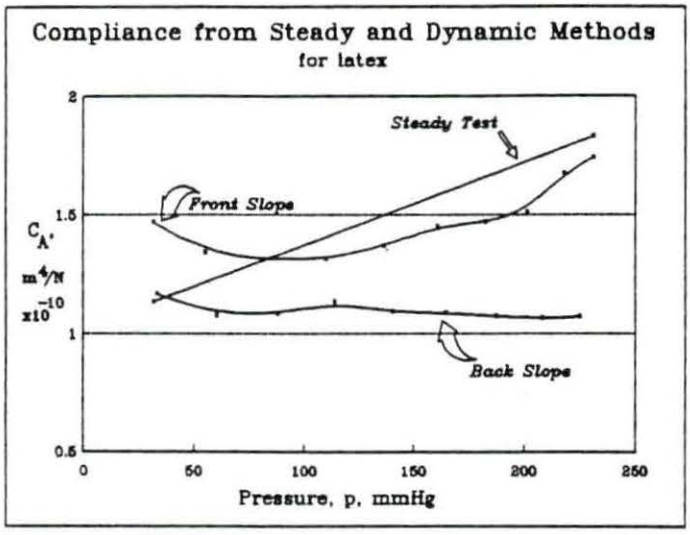

Figure 6.9: Comparison of compliance as a function of pressure from the steady and the dynamic infusion techniques on a *latex segment*

how C_A varies with p for the steady and dynamic tests. Ideally, the three values of compliance for each pressure should be the same.

Similar data were obtained for latex samples, however, the comparison between the steady and dynamic techniques give closer agreement for the latex than for the artery (see Figure 6.9). Notice that the vertical scaling on Figures 6.7 and 6.9 are different. Table 6.3 shows numerically the difference between the steady and dynamic infusion techniques for two arterial and one latex sample. Notice that in the physiological pressure region (around $p = 100$ mmHg), there is better agreement between the dynamic technique using the front slope of the wave rather than the back slope. Also, the latex sample tends to show closer overall agreement for both techniques than the arterial sample. The data from Dog #4 have much lower values

Table 6.3: Comparison of steady and dynamic infusion techniques for an arterial and latex sample at selected physiological pressures. $\Delta\%$ indicates the percent difference between the dynamic technique using the front or back slope value with respect to the steady value

	Compliance, C_A, $\frac{m^4}{N} \times 10^{-10}$				
	for Arterial Sample (Dog #2)				
	Steady Technique	Dynamic Technique			
		front	$\Delta\%$	back	$\Delta\%$
p = 80 mmHg	4.01	2.95	-26.4	1.93	-51.9
p = 100 mmHg	3.60	3.25	-9.70	1.70	-52.8
p = 120 mmHg	2.91	3.45	18.6	1.46	-49.8
	for Arterial Sample (Dog #4)				
p = 80 mmHg	3.46	3.57	3.18	2.84	-17.9
p = 100 mmHg	3.34	3.48	4.19	2.76	-17.4
p = 120 mmHg	3.19	3.44	7.84	2.73	-14.4
	for Latex Sample				
p = 80 mmHg	1.29	1.32	2.3	1.08	-16.3
p = 100 mmHg	1.36	1.32	-2.9	1.11	-14.0
p = 120 mmHg	1.44	1.34	-6.9	1.12	-22.2

for $\Delta\%$ than from Dog #2. This is probably due in part to increased efficiency in sample preparations and experimental testing.

7 CONCLUSIONS

There have been two different techniques used in this research to determine the compliance of a given tubular material. They are:

- the steady infusion technique, and
- the dynamic infusion technique.

The steady infusion technique involved gradually infusing a fluid into a compliant tube and plotting the change in area *vs.* pressure. The compliance was determined from the slope of this curve. The dynamic infusion technique involved the use of a pulsatile flow pump to simulate the actual *in vivo* pressure and flow waves into a compliant tube with no net flow. Both techniques gave similar results.

It has been found that in the conventional steady infusion technique, it is possible to get approximate values for compliance *in vitro*. These compliance values were used as the standard for which the results of the dynamic infusion technique were judged. However, the steady infusion technique is inappropriate for clinical use because it involves excising the arterial segment. It would be a useful method, however, in the design and evaluation of artificial arterial prosthetic devices.

In addition, more extensive measurements should be carried out on the latex material to determine a precise modulus of elasticity and how the modulus changes

with pressure. One of the principal methods used to verify the results of the steady infusion technique was calculating E_{inc} from Equation 3.6 (which is only an approximation), and comparing it to similar values available in the literature. As seen in Section 6.1, however, the modulus for latex can be variable and difficult to compare. Therefore, the literature values should be used only for very general comparisons; the actual values can vary by an order of magnitude (or greater).

Existing *in vivo* techniques for determining compliance have usually relied on measuring small changes in the diameter of the artery which is typically on the order of a few percent. Measuring the change in area (or volume), however, seems to be easier since the changes are approximately an order of magnitude larger. By using the dynamic model, an approximate arterial compliance can be obtained by tracking the flow and pressure waveforms which may be more easily measured than changes in internal diameter of an artery. Although the quantity of data collected is somewhat limited, the results of the two techniques seem to compare favorably for both the latex and arterial samples. Obviously, more data need to be collected to show whether or not the dynamic model is reliable or reproducible. The purpose in this study was to determine the feasibility of the technique, and based on the preliminary results, it is feasible. In addition to collecting more data, it would be of interest to try to determine the reasons for the differences between compliance values obtained using the front and back slopes of the waves in the dynamic technique. Also, modified *in vivo* tests could be run where the actual flow and pressure waves are generated naturally by the heart using intact arterial samples.

At the present time, applications of this dynamic model would be invasive. However, with Doppler ultrasound techniques, it is possible to measure instantaneous flow in a superficial artery. Thus, the limiting factor is the technology for measuring instantaneous pressure. It is felt that in the future, it will be possible to measure pressure noninvasively (Yamakoshi, Rolfe and Murphy, 1988), so the dynamic technique could possibly be used in the clinical situation. One possible implementation of this method would be to occlude the blood flow at the wrist and measure the flow and pressure at the elbow. Since it has been shown that there is a correlation between certain disease states and changes in arterial compliance, this research should have clinical significance.

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This research is dedicated to all the people in my life who have helped me to get where I am today. I shall *never* forget you, one and all.

10 APPENDIX A: TYRODES SOLUTION

Below are the ingredients and quantities used to make the Tyrodes solution in which the arterial grafts are placed temporarily after excision and prior to testing.

Table 10.1: Recipe for Tyrodes solution

Ingredient	Concentration, mM
NaCl	137
KCl	2.68
$CaCl_2$	1.80
$MgCl_2$	0.53
$NaHCO_3$	11.9
NaH_2PO_4	0.33
Glucose	5.60

11 APPENDIX B: MEASURED PHYSICAL PARAMETERS

Table 11.1: Measured physical parameters for latex and canine samples

	Length, l, cm	Dog Weight W, kg	Outer diameter, d_o, cm	Wall thickness, t, mm	Inner diameter, d_i, cm	h/d_i ratio	Comments
Latex	8.32	—	0.612	0.356	0.576	0.062	
Dog #1	6.93	65	0.549	0.526	0.496	0.106	C_A not determined - excessive testing
Dog #2	5.84	57	0.548	0.401	0.508	0.079	
Dog #3	7.09	72	0.852	0.652	0.786	0.083	C_A not determined - leaky vessel
Dog #4	6.35	57	0.683	0.438	0.584	0.075	

12 APPENDIX C: COLLECT BATCH FILE

COLLECT is the *master* batch file responsible for controlling all the other batch files including CALIBRAT, STEADY, DYNAMIC and CLEANSAS.

```
REM BATCH FILE CALLED 'A:COLLECT.BAT'
CLS
REM COMPLIANCE TESTING ROUTINE UTILIZING BOTH THE STEADY AND
REM DYNAMIC INFUSION METHODS. MAKE SURE YOUR SYSTEM DISK IS
REM IN A: AND YOUR DATA DISK IS IN B:
ECHO OFF
A:\CALIBRAT
A:\STEADY
A:\DYNAMIC
A:\CLEANSAS
ECHO ON
CLS
C:
REM COMPLIANCE EVALUATION COMPLETE
REM NORMAL TERMINATION
```

13 APPENDIX D: CALIBRATION SOFTWARE

CALIBRAT is the first batch file to be executed by COLLECT. It is responsible for executing the diagnostics and then calibrating the pressure and flow transducers. Following CALIBRAT is the source code for the programs that CALIBRAT runs.

```
REM BATCH FILE CALLED 'A:CALIBRAT.BAT'
CLS
REM CALIBRATION AND EQUIPMENT CHECK
ECHO OFF
C:\PROGLANG\BASIC\INTRPT\BASICA A:VOLTCHK.BAS
C:\PROGLANG\BASIC\INTRPT\BASICA A:TESTSWIT.BAS
C:\PROGLANG\BASIC\INTRPT\BASICA A:PRESCAL.BAS
B:
C:\SAS\SAS A:PRESCAL.SAS
PRINT B:\PRESCAL.LST
C:\PROGLANG\BASIC\INTRPT\BASICA A:FLOWCAL.BAS
B:
C:\SAS\SAS A:FLOWCAL.SAS
PRINT B:\FLOWCAL.LST
ECHO ON
A:\CLEANSAS.BAT
CLS
A:
REM CALIBRATION COMPLETE - TYPE 'STEADY' FOR STEADY INFUSION
METHOD
```

VOLTCHK.BAS is the basic program responsible for verifying that the voltage

coming out of the Grass recorder is the same as the voltage being reported by the PC. This is extremely important because the Keithley is used for other research projects and therefore the internal settings get changed.

```
100 'KEITHLEY TO PC/AT VOLTAGE VERIFACATION (called VOLTCHK)
110 CLEAR:CLS:KEY OFF:BEEP
120 LOCATE 10,10:PRINT "Connect voltage supply and volt meter
        to Keithley."
130 LOCATE 12,10:INPUT "Press ENTER to continue.";X$
140 CLS
150 DEF SEG = &HCFF8
160 LOCATE 10,20:PRINT "Type 'C' to Continue"
170 A$=INKEY$
180 IF A$="C" OR A$="c" THEN 240
190 POKE 1,6:POKE 26,0
200 POKE 10,0:POKE 24,0
210 P=(256x(PEEK(3)-240)+PEEK(2)-2047)x20/4096  'p in volts
220 LOCATE 15,20:PRINT USING "CURRENT VOLTAGE THRU A/D =
        ##.### Volts";P
230 GOTO 170
240 CLS
250 LOCATE 10,15:PRINT "Voltage verification complete."
260 LOCATE 12,15:PRINT "Now proceeding to relay check."
270 PRINT:PRINT
280 SYSTEM
```

TESTSWIT.BAS is the basic program responsible for making sure the mechanical relay switch controlling the infusion pump is working properly.

```
100 'MECHANICAL RELAY TESTING (called TESTSWIT)
110 CLEAR:CLS:KEY OFF
120 DEF SEG = &HCFF8
130 LOCATE 8,10:PRINT "Mechanical Relay Stitch Test."
140 LOCATE 10,10:PRINT "Verify operation by turning on and
```

```
        off several times."
150 LOCATE 12,10:PRINT "ENTER (0) PUMP OFF / (1) PUMP ON /
        (2) END "
160 A$=INKEY$
170 IF A$="0" THEN 210
180 IF A$="1" THEN 230
190 IF A$="2" THEN 250
200 GOTO 160
210 POKE 8,0
220 GOTO 150
230 POKE 8,1
240 GOTO 150
250 CLS
260 LOCATE 14,10:PRINT "Relay verification complete."
270 LOCATE 16,10:PRINT "Now proceeding to PRESSURE TRANSDUCER
        CALIBRATION."
280 PRINT:PRINT
290 SYSTEM
```

PRESCAL.BAS is the basic program responsible for calibrating the pressure transducer.

```
100 ' CALIBRATION SET-UP (called PRESCAL.BAS)
110 '
120 DIM W(25),WW(25),P(25),V(25),S(25),V0(1000),ST(1000)
130 BEEP:BEEP:BEEP
140 ON ERROR GOTO 1340
150 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
160 'SET UP
170 CLS:KEY OFF
180 PRINT:PRINT "CALIBRATION SET-UP ROUTINE":PRINT
190 PRINT "PROGRAM DISK IN DRIVE A."
200 PRINT "DATA DISK IN DRIVE B."
210 PRINT
220 PRINT "PRINTER ON AND ON LINE."
230 PRINT
240 INPUT "Enter calibration file name (i.e.,
```

```
        'B:PRESCAL.DAT')";F$
250 PRINT
260 INPUT "ENTER TRANSDUCER HEIGHT IN CM";H
270 PRINT
280 N=1
290 CLS
300 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
310 'KEITHLEY SET-UP
320 DEFINT N: DIM D(500)
330 DEF SEG=&HCFF8
340 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
350 'PRESSURE AND VOLTAGE
360 BEEP
370 PRINT
380 PRINT "FOR ATM PRESSURE ENTER TRANSDUCER HEIGHT
        =";H;"CM."
390 INPUT "ENTER WATER HEIGHT IN CM (TYPE -1 TO END)";W(N)
400 IF W(N)=-1 THEN 680
410 WW(N)=W(N)-H
420 P(N)=WW(N)x1.36
430 FOR M=0 TO 100
440 POKE 1,6:POKE 26,0:POKE 10,0:POKE 24,0
450 D(M)=(256x(PEEK(3)-240)+PEEK(2)-2047)x20/4096 'd(m) in
        volts
460 'voltage range/number of channels
470 B=3.44x4.44
480 B=123.3x3.45
490 NEXT M
500 TOT=0
510 FOR M=1 TO 100
520 TOT=D(M)+TOT
530 NEXT M
540 V(N)=TOT/100
550 GOSUB 1530
560 S(N)=SQR(S2)
570 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
580 'SCREEN OUTPUT
590 PRINT TAB(25):PRINT "ACTUAL PRESSURE HEAD =";WW(N);"cm
        H2O"
```

```
600 PRINT TAB(25):PRINT "CORRESPONDING PRESSURE
      =";P(N);"mmHg."
610 PRINT TAB(30):PRINT "VOLTAGE = ";V(N);"V"
620 PRINT TAB(30):PRINT "STANDARD DEVIATION = ";S(N)
630 PRINT TAB(25):PRINT "TOTAL NUMBER OF POINTS SO FAR =";N+1
640 PRINT
650 IF S(N)>.1 THEN INPUT "TRANSDUCER INSTABILITY!!! NEW
      PT<>";YN$:GOTO 350
660 N=N+1
670 GOTO 350
680 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
690 'DATA DISPLAY
700 CLS
710 LOCATE 12,2:PRINT "Total number of calibration points is
      ";N;"."
720 IF N<10 THEN LOCATE 14,2:PRINT "YOU NEED >= 10 POINTS FOR
      CALIBRATION"
730 LOCATE 16,2:INPUT "Do you want to recalibrate <NO>";NY$
740 CLS:PRINT:PRINT
750 IF NY$<>"" THEN N=1:CLS:CLEAR:GOTO 150
760 PRINT       "HEAD    PRESSURE  VOLTAGE   DEVIATION"
770 PRINT       " cm       mmHg      mV                "
780 PRINT       "----    --------  -------   ---------"
790 FOR J=0 TO N-1
800 PRINT USING "##.#     ##.##     #.###      .####";
      WW(J),P(J),V(J),S(J)
810 NEXT
820 PRINT :PRINT
830 INPUT "Do you want a hard copy <NO>";R$
840 IF R$="" THEN 950
850 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
860 'HARD COPY
870 LPRINT "FOR TRANSDUCER AT HEIGHT = ";H;"cm."
880 LPRINT
890 LPRINT       "HEAD    PRESSURE  VOLTAGE   DEVIATION"
900 LPRINT       " cm       mmHg      mV                "
910 LPRINT       "----    --------  -------   ---------"
920 FOR J=0 TO N-1
930 LPRINT USING "##.#     ##.##     #.###      .####";
```

```
        WW(J),P(J),V(J),S(J)
940 NEXT J
950 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
960 'DATA STORED TO OUTPUT FILE 'CALDATA'
970 PRINT:PRINT "Do you want to store data as '";F$;"'":INPUT
        "<yes>";Y$
980 IF Y$<>"" THEN 1240
990 OPEN F$ FOR OUTPUT AS #1
1000 FOR J=0 TO N-1
1010 PRINT #1, USING "###.#  ###.##  ##.###  #.####";
         WW(J),P(J),V(J),S(J)
1020 NEXT J
1030 CLOSE
1040 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1050 'DATA RETRIEVAL FROM DISK AND DISPLAY
1060 CLS
1070 LOCATE 12,2:PRINT "Total number of calibration points is
        ";N;"."
1080 LOCATE 16,2
1090 INPUT"Do you want to retrieve data to verify storage
        (<>=yes)";YN$
1100 IF YN$<>"" THEN 1240
1110 CLS
1120 OPEN F$ FOR INPUT AS #1
1130 LOCATE 8,1:PRINT "Data from ";F$
1140 LOCATE 10,1
1150 PRINT       "HEAD    PRESSURE  VOLTAGE   DEVIATION"
1160 PRINT       " cm       mmHg      mV                "
1170 PRINT       "----    --------  -------   ---------"
1180 FOR J=1 TO N
1190 INPUT #1, WW(J),P(J),V(J),S(J)
1200 PRINT USING "##.#     ##.##     #.###       .####";
        WW(J),P(J),V(J),S(J)
1210 NEXT
1220 CLOSE
1230 PRINT :PRINT
1240 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1250 'ENTER DOS
1260 INPUT "Do you want to 'shell' out of BASIC into DOS
```

```
        <NO>";YN$
1270 IF YN$="" THEN 1440
1280 CLS
1290 BEEP:BEEP
1300 LOCATE 10,2:PRINT "Entering DOS (type 'EXIT' to return
        to program)"
1310 SHELL
1320 CLS
1330 GOTO 1440
1340 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
1350 'ERROR TRAP
1360 FOR X=1 TO 5
1370 T=TIMER
1380 CLS
1390 WHILE (TIMER-T)<1
1400 BEEP
1410 LOCATE 10,10:PRINT "ERROR TRAP ACTIVATED!!!"
1420 WEND
1430 NEXT
1440 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
1450 'END OF CALIBRATION
1460 BEEP:BEEP:BEEP:CLS
1470 LOCATE 12,10:PRINT "Normal end of calibration
        procedure."
1480 PRINT
1490 LOCATE 14,10:PRINT "Entering SAS to get linear
        regression."
1500 LOCATE 16,10:PRINT "Use this time to set up for
        infusion."
1510 PRINT:PRINT
1520 SYSTEM
1530 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
1540 'SUBROUTINE TO CALCULATE STANDARD DEVIATION
1550 S2=0
1560 FOR Z=1 TO 100
1570 S2=((D(Z)^2-V(N)^2)/99)+S2
1580 NEXT Z
1590 RETURN
1600 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

PRESCAL.SAS is the SAS program responsible for doing the calibration linear regression to determine the conversion from volts to mmHg. It also plots the pressure *vs.* voltage and determines the correlation coefficient.

```
/+ PRESSURE TRANSDUCER CALIBRATION called 'PRESCAL.SAS' +/

LIBNAME PRESCAL 'B:';

OPTIONS PAGESIZE=60;

DATA PRESCAL;
   INFILE 'B:PRESCAL.DAT' PAD;
   INPUT HEAD 1-6 PRESSURE 7-14 VOLTAGE 15-22 STDDEV 23-30;
RUN;

PROC PRINT DATA=PRESCAL;
RUN;

PROC REG OUTEST=PRESCAL.OUT;
   MODEL PRESSURE=VOLTAGE / P R CLI CLM;
RUN;

GOPTIONS DEVICE=EGAL;

SYMBOL1 CV=GREEN V=PLUS
        CI=BLUE  I=RL;

AXIS1 LABEL=(R=0 A=90 H=0.75 CM) VALUE=(H=0.4 CM);
AXIS2 LABEL=(H=0.75 CM) VALUE=(H=0.4 CM);

PROC GPLOT DATA=PRESCAL;
   PLOT PRESSURExVOLTAGE=1 / GRID VAXIS=AXIS1 HAXIS=AXIS2;
   TITLE1 H=1 CM 'PRESSURE TRANSDUCER CALIBRATION';
   TITLE3 H=0.5 CM 'Pressure VS. Voltage';
   LABEL PRESSURE='Pressure, mmHg' VOLTAGE='Voltage, V,
```

```
       volts';
RUN;
```

FLOWCAL.BAS is the basic program responsible for calibrating the flow probe transducer.

```
100 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
110 'FLOW METER CALIBRATION (called FLOWCAL)
120 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
130 'INTRODUCTION
140 ON ERROR GOTO 1340
150 CLEAR:CLOSE
160 C = 1
170 DIM Q(3000), AVGVOLT(20), ACTVOL(20), ACTTIME(20),
        ACTFLOW(20)
180 B=125                   'b is DC shift parameter for pset
190 Z=100                   'amplification factor
200                         'for voltage b=125
210 KEY OFF:CLS:SCREEN 2
220 LOCATE 8,10:PRINT "+++ FLOW METER CALIBRATION ROUTINE
        +++"
230 LOCATE 11,13:PRINT "Type 1 to CALIBRATE METER"
240 LOCATE 15,13:PRINT "Type 9 to EXIT PROGRAM"
250 BEEP
260 A$=INKEY$
270 IF A$="1" THEN 300
280 IF A$="9" THEN 1260
290 GOTO 260
300 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
310 'SET UP & INITIALIZATION
320 CLS
330 LOCATE 3,10:PRINT "+++ FLOW METER CALIBRATION +++"
340 LOCATE 5,10:PRINT "Make certain all connections are
        correct."
350 BEEP
360 LOCATE 7,10:INPUT "Are you ready to proceed with
        calibration <yes>";YN$
```

```
370 IF YN$<>"" THEN 120
380 CLS
390 LOCATE 3,10:PRINT "Turn on and maintain CONSTANT flow."
400 BEEP
410 LOCATE 5,10:PRINT "Press 'C' when steady state is
        achieved."
420 A$=INKEY$
430 IF A$="C" OR A$="c" THEN 450
440 GOTO 420
450 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
460 'CHANNEL 1 - FLOW CALIBRATION
470 CLS
480 LOCATE  5,30:PRINT "Nominal time = 15 sec."
490 LOCATE 20,30:PRINT "Channel 1 = Flow Wave"
500 DEF SEG = &HCFF8
510 POKE 1,6:POKE 26,0
520 J=1                         'j=number of samples collected
530 T=TIMER
540 WHILE (TIMER-T)<13
550     FOR N=0 TO 610          'horizontal scrolling (n=610)
560         POKE 10,1           'channel selection = 1(flow)
570         POKE 24,0
580         Q(J)=(256x(PEEK(3)-240)+PEEK(2)-2047)x20/4096
590         PSET(N,B-Q(J)xZ)
600         J=J+1
610     NEXT
620 WEND
630 ACTTIME(C)=(TIMER-T)
640 BEEP
650 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
660 'VOLTAGE ANALYSIS AND CALIBRATION SUMMARY
670 CLS
680 LOCATE 5,10:PRINT "Averaging voltage values, please
        wait..."
690 TOT=0
700 FOR N=1 TO J
710     TOT = Q(N) + TOT
720 NEXT
730 AVGVOLT(C) = TOT/J
```

```
740 CLS
750 LOCATE 7,10:PRINT "Averaging complete."
760 BEEP
770 LOCATE 9,10
780 INPUT "Volume of fluid collected during calibration
        (cm3)";ACTVOL(C)
790 ACTVOL(C)=ACTVOL(C)x1000  'mm3
800 CLS
810 LOCATE  7,10:PRINT USING "Number of calibrations = #";C
820 LOCATE  9,10:PRINT USING "Average voltage = ##.####
        V";AVGVOLT(C)
830 LOCATE 11,10:PRINT USING "Actual volume = ######.##
        mm3";ACTVOL(C)
840 LOCATE 13,10:PRINT USING "Time ellapsed = ##.##
        secs";ACTTIME(C)
850 LOCATE 15,10
860 ACTFLOW(C)=ACTVOL(C)/ACTTIME(C)
870 PRINT USING "Calculated volumetric flowrate = ######.##
        mm3/s";ACTFLOW(C)
880 LOCATE 17,10:INPUT "Do you wish to calibrate another
        point <yes>";YN$
890 IF YN$ = "" THEN C = C + 1: GOTO 380
900 IF C>10 THEN 940
910 LOCATE 20,10:PRINT "A MINIMUM OF 10 CALIBRATION POINTS
        ARE RECOMMENDED!!!"
920 LOCATE 22,10:INPUT "Do you wish to calibrate another
        point <yes>";YN$
930 IF YN$ = "" THEN C = C + 1: GOTO 380
940 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
950 'STORE CALIBRATION DATA TO DISK
960 CLS
970 LOCATE 10,10:PRINT USING "Calibration complete. # points
        collected";C
980 LOCATE 12,10:INPUT"Do you want to save calibration data
        to disk <yes>";YN$
990 IF YN$<>"" THEN 120
1000 LOCATE 14,10
1010 INPUT "Enter name of file for summary data storage
        ('B:FLOWCAL1.DAT')";F$
```

```
1020 OPEN F$ FOR OUTPUT AS #1
1030 FOR X=1 TO C
1040 PRINT#1, USING "##  #.####  ####.##  ##.##  ####.##";
        X, AVGVOLT(X), ACTVOL(X), ACTTIME(X), ACTFLOW(X)
1050 NEXT
1060 CLOSE
1070 '++++++++++++++++++++++++++++++++++++++++++++++++++++
1080 'SUMMARY OF FLOW CALIBRATION INFO
1090 CLS
1100 LOCATE 10,10:PRINT "Summary data stored to ";F$
1110 LOCATE 12,10:PRINT "Here is summary information from
        ";F$
1120 PRINT
1130 PRINT "Trial     Voltage     Volume     Time
        Flowrate"
1140 PRINT "-----     -------     ------     ----
        --------"
1150 PRINT
1160 OPEN F$ FOR INPUT AS #1
1170 FOR X=1 TO C
1180 INPUT #1, X, AVGVOLT(X), ACTVOL(X), ACTTIME(X),
        ACTFLOW(X)
1190 PRINT USING " ##        ##.##      ####.##    ##.##
        ####.##";X, AVGVOLT(X), ACTVOL(X), ACTTIME(X),
        ACTFLOW(X)
1200 NEXT
1210 BEEP
1220 PRINT :PRINT "Press 'C' to CONTINUE."
1230 A$=INKEY$
1240 IF A$="C" OR A$="c" THEN 120
1250 GOTO 1230
1260 '++++++++++++++++++++++++++++++++++++++++++++++++++++
1270 'END OF FLOW METER CALIBRATION
1280 CLS
1290 BEEP:BEEP:SCREEN 0
1300 LOCATE 8,13:PRINT "Normal Termination - Program
        Complete."
1310 LOCATE 10,13:PRINT "Entering SAS to run linear
        regression."
```

```
1320 LOCATE 12,13:PRINT "Use this time to set up for DYNAMIC
        TESTING."
1330 CLOSE:PRINT :PRINT :PRINT :SYSTEM
1340 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1350 'ERROR TRAP
1360 FOR X=1 TO 5
1370 T=TIMER
1380 CLS
1390 WHILE (TIMER-T)<1
1400 BEEP
1410 LOCATE 10,10:PRINT "ERROR TRAP ACTIVATED!!!"
1420 WEND
1430 NEXT
1440 GOTO 120
1450 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

FLOWCAL.SAS is the SAS program responsible for doing the calibration linear regression to determine the conversion from volts to cm^3/min. It also plots the flow rate *vs.* voltage and determines the correlation coefficient.

```
/+  FLOW METER CALIBRATION called 'FLOWCAL.SAS'  +/

LIBNAME FLOWCAL 'B:';

OPTIONS PAGESIZE=60;

DATA FLOWCAL;
   INFILE 'B:FLOWCAL1.DAT' PAD;
   INPUT N 1-3 VOLTAGE 4-11 VOL 12-20 TIME 21-27 FLOW 28-36;
RUN;

PROC PRINT DATA=FLOWCAL;
RUN;

PROC REG OUTEST=FLOWCAL.OUT;
   MODEL FLOW=VOLTAGE / P R CLI CLM;
```

```
RUN;

GOPTIONS DEVICE=EGAL;

SYMBOL1 CV=GREEN V=PLUS
        CI=BLUE I=RL;

AXIS1 LABEL=(R=0 A=90 H=0.75 CM) VALUE=(H=0.4 CM);
AXIS2 LABEL=(H=0.75 CM) VALUE=(H=0.4 CM);

PROC GPLOT DATA=FLOWCAL;
   PLOT FLOWxVOLTAGE=1 / GRID VAXIS=AXIS1 HAXIS=AXIS2;
   TITLE1 H=1 CM 'FLOW METER CALIBRATION';
   TITLE3 H=0.5 CM 'Flow Rate VS. Voltage';
   LABEL FLOW='Flow Rate, mm3/sec' VOLTAGE='Voltage, V,
        Volts';
RUN;
```

14 APPENDIX E: STEADY INFUSION SOFTWARE

STEADY is the next batch file to be executed by COLLECT. It is responsible for executing the steady infusion testing, storing the data and displaying it to the screen. Following STEADY is the source code for the programs that STEADY runs.

```
CLS
REM STEADY INFUSION TESTING ROUTINE
ECHO OFF
C:\PROGLANG\BASIC\INTRPT\BASICA A:COMPLI.BAS
B:
C:\SAS\SAS A:COMPLI.SAS
PRINT B:\COMPLI.LST
C:\PROGLANG\BASIC\INTRPT\BASICA A:CALC.BAS
ECHO ON
CLS
A:
REM PROCEDURE COMPLETE - CONTINUING ON TO DYNAMIC INFUSION
REM METHOD
```

COMPLI.BAS is the BASIC program responsible for executing the steady infusion procedure. It automatically controls the steady infusion pump and the acquisition and filtering of the pressure and area data.

```
100 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
110 'DATA ACQUISITION AND COLLECTION AFTER CALIBRATION
```

```
        (called COMPLI.BAS)
120 CLEAR
130 DIM X(1000),P(1000),XX(1000)
140 DEFINT N:DIM D(5000)
150 CLS:KEY OFF
160 ON ERROR GOTO 1560
170 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
180 'SET UP
190 CLS
200 CLOSE
210 BEEP:BEEP:BEEP
220 PRINT :PRINT "DATA ACQUSITION ROUTINE (assumes
        calibration comlpete)":PRINT
230 PRINT "PROGRAM DISK IN DRIVE A."
240 PRINT "DATA DISK IN DRIVE B."
250 PRINT
260 PRINT "PRINTER ON AND ON LINE."
270 LOCATE 10,10:PRINT "+++ STATIC COMPLIANCE TESTING ROUTINE
        +++"
280 LOCATE 13,13:PRINT "Type 1 to ENTER PRESSURE CONVERSION
        FACTORS"
290 LOCATE 14,13:PRINT "               AND PHYSICAL
        PARAMETERS"
300 LOCATE 16,13:PRINT "Type 2 to COLLECT DATA"
310 LOCATE 18,13:PRINT "Type 9 to EXIT PROGRAM"
320 BEEP
330 A$=INKEY$
340 IF A$="1" THEN 380
350 IF A$="2" THEN 490
360 IF A$="9" THEN 1760
370 GOTO 330
380 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
390 'ENTER CONVERSION FACTORS
400 CLS
410 LOCATE 10,1:PRINT "Enter linear regression results from
SAS analysis."
420 LOCATE 12,20:INPUT "Intercept Value ==>";INTER
430 LOCATE 14,20:INPUT "Slope Value ==>";SLOPE
440 LOCATE 18,1:INPUT "Enter piston velocity of infusion pump
```

```
        (cm/s)";VEL
450 LOCATE 20,1:INPUT "Enter maximum distance traversed by
        piston (cm)";DIST
460 LOCATE 22,1:INPUT "Enter length of arterial segment
        (cm)";LENGTH
470 LOCATE 24,1:INPUT "Enter INTERNAL diameter of arterial
        segment (AT REFFERENCE PRESSURE) (cm)";DIAM
480 GOTO 170
490 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
500 'PUMP SET-UP
510 BEEP
520 CLS
530 LOCATE 6,10:PRINT "CONNECT INFUSION PUMP TO RELAY TO
        DIGITAL OUTPUT."
540 LOCATE 8,15:PRINT "POSITION PISTON VIA KEYBOARD CONTROL."
550 LOCATE 10,25:PRINT "MECHANICAL RELAY OPERATION"
560 LOCATE 12,20:PRINT "'F' = PUMP ON   /   'S' = PUMP OFF"
570 LOCATE 14,28:PRINT "'C' = CONTINUE"
580 LOCATE 16,28:PRINT "'E' = EXIT to MAIN MENU"
590 DEF SEG=&HCFF8
600 A$ = INKEY$
610 IF A$="F" OR A$="f" THEN 660
620 IF A$="S" OR A$="s" THEN 680
630 IF A$="C" OR A$="c" THEN 700
640 IF A$="E" OR A$="e" THEN 170
650 GOTO 600
660 POKE 8,1                                        'pump on
670 GOTO 600
680 POKE 8,0                                        'pump off
690 GOTO 600
700 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
710 'PRESSURE (VOLTAGE) AND VOLUME MEASUREMENT
720 CLS
730 POKE 8,0
740 DEF SEG = &HCFF8
750 LOCATE 10,10:PRINT "PUMP IS ON - PRESSURE AND VOLUME ARE
        BEING RECORDED."
760 J=0:E=0
770 T=TIMER                                 'start time
```

```
780 POKE 8,1                                    'pump on
790 WHILE VELx(TIMER-T)<DIST
800     E=E+1
810     IF E>10 THEN 820 ELSE 850
820          LOCATE 13,10
830          PRINT USING "TIME REMAINING = ####.#
                 SECS.";(DIST/VEL)-(TIMER-T)
840          E=0
850     J=J+1                              'j=total number of samples
860     POKE 1,6:POKE 26,0:POKE 10,0:POKE 24,0
870     D(J)=(256x(PEEK(3)-240)+PEEK(2)-2047)x20/4096
            'd(j) in volts
880     X(J)=VELx(TIMER-T)/5.842/LENGTHx100  'x(j)=A-Ao ,
           sqmm   (1cc=5.842cm)
890     F=TIMER
900     IF (TIMER-F)<.2 THEN 900             'sampling rate=2Hz
910 WEND
920 POKE 8,0                                    'pump off
930 TT=TIMER                                    'stop time
940 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
950 'DATA FILTERING (LOW PASS 5-POINT MOVING AVERAGE FILTER)
960 CLS
970 LOCATE 12,10:PRINT "PUMP IS OFF - DATA IS BEING
        FILTERED."
980 K=1: C=0
990 FOR P=1 TO J STEP 5
1000  C=C+1
1010  M=0: Q=0
1020  FOR I=K TO K+4
1030  M=M+D(I)
1040  Q=Q+X(I)
1050  NEXT I
1060  D(C)=M/5           'c=number of points after filtering
1070  X(C)=Q/5
1080  K=K+5
1090 NEXT P
1100 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1110 'CONVERSION
1120 DIAMMM=DIAMx10
```

```
1130 FOR Y=1 TO C
1140 P(Y)=SLOPExD(Y)+INTER            'p(y)=pressure in mmHg
1150 XX(Y)=X(Y)/(3.1415x(DIAMMM/2)^2)x100
          'xx(y)=(A-Ao)/Aref, per cent
1160 NEXT Y
1170 '+++++++++++++++++++++++++++++++++++++++++++++++++++++
1180 'CALCULATIONS
1190 ACTTIME=(TT-T)                    'actual infusion time
1200 ACTDIST=VELxACTTIME    'actdist=actual distance infused
1210 CVOL=ACTDIST/5.842              'cvol=fluid volume added
1220 SEGVOL=(3.1415x(DIAM/2)^2)xLENGTH      'segvol=original
        segment volume
1230 CHAVOL=CVOL/SEGVOLx100   'chavol=percent change segment
1240 '+++++++++++++++++++++++++++++++++++++++++++++++++++++
1250 'SCREEN OUTPUT
1260 CLS
1270 LOCATE 10,15:PRINT "TIME OF INFUSION        =
        ";ACTTIME;"SECS."
1280 LOCATE 12,15:PRINT "DISTANCE OF INFUSION    =
        ";ACTDIST;"CM."
1290 LOCATE 14,15:PRINT "VOLUME OF INFUSION      =
        ";CVOL;"CC."
1300 LOCATE 16,15
1310 PRINT USING "PERCENT INCREASE OF SEGMENT VOLUME = ###.#
        %";CHAVOL
1320 LOCATE 18,15:PRINT "TOTAL NUMBER OF FILTERED POINTS =
        ";C
1330 LOCATE 20,15:PRINT "LENGTH OF SEGMENT = ";LENGTH;"CM"
1340 '+++++++++++++++++++++++++++++++++++++++++++++++++++++
1350 'SCREEN DUMP OF USEFUL INFO
1360 LOCATE 20,1:INPUT "Do you want a hard copy of the above
        data <yes>";YN$
1370 IF YN$<>"" THEN 1440
1380 LPRINT "TIME OF INFUSION        = ";ACTTIME;"SECS."
1390 LPRINT:LPRINT "DISTANCE OF INFUSION    = ";ACTDIST;"CM."
1400 LPRINT:LPRINT "VOLUME OF INFUSION      = ";CVOL;"CC."
1410 LPRINT:LPRINT USING "PERCENT INCREASE OF SEGMENT VOLUME
        = ###.# %";CHAVOL
1420 LPRINT:LPRINT "TOTAL NUMBER OF FILTERED POINTS = ";C
```

```
1430 LPRINT:LPRINT "LENGTH OF SEGMENT = ";LENGTH;"CM"
1440 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1450 'DATA STORED TO OUTPUT FILE 'COMPLI.DAT'
1460 BEEP
1470 PRINT:INPUT "Do you want to store data as 'B:COMPLI.DAT'
        <YES>";Y$
1480 IF Y$<>"" THEN 1550
1490 OPEN "B:COMPLI.DAT" FOR OUTPUT AS #1
1500 FOR M=0 TO C-1
1510 PRINT #1, USING "###.##     ##.###     ###.##";
        P(M),X(M),XX(M)
1520 NEXT
1530 CLOSE
1540 PRINT:PRINT "Data have been stored as 'B:COMPLI.DAT'
1550 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1560 'ENTER DOS
1570 INPUT "Do you want to 'shell' out of BASIC into DOS
        <NO>";YN$
1580 IF YN$="" THEN 170
1590 CLS
1600 BEEP:BEEP
1610 LOCATE 10,2:PRINT "Entering DOS (type 'EXIT' to return
        to program)"
1620 SHELL
1630 CLS
1640 GOTO 170
1650 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1660 'ERROR TRAP
1670 FOR X=1 TO 5
1680 T=TIMER
1690 CLS
1700 WHILE (TIMER-T)<1
1710 BEEP
1720 LOCATE 10,10:PRINT "ERROR TRAP ACTIVATED!!!"
1730 WEND
1740 NEXT
1750 GOTO 170
1760 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1770 'END OF DATA ACQUISITION
```

```
1780 BEEP:BEEP:BEEP:CLS
1790 LOCATE 12,10:PRINT "Normal end of acquisition
        procedure."
1800 PRINT
1810 PRINT
1820 LOCATE 14,10:PRINT "Running SAS to plot compliance."
1830 LOCATE 16,10:PRINT "Use this time to set up for dynamic
        testing."
1840 SYSTEM
1850 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

COMPLI.SAS is a SAS routine that fits a curve of the form

$$A - A_0 = c_1 p^2 + c_2 p + c_3 \tag{14.1}$$

to the data collected by COMPLI.BAS, determines the constants, and displays $A - A_0$ and $\frac{A-A_0}{A_{ref}}$ *vs.* pressure. Next, it determines the derivative of Equation 14.1 and plots $\frac{d(A-A_0)}{dp}$ and generates a second plot of C_A *vs.* p. Finally, a statistical analysis is performed and the results are outputted to the printer.

```
/+ COMPLIANCE PLOTS TO SCREEN called 'COMPLI.SAS' +/

OPTIONS PAGESIZE=60;

DATA COMPLI;
   INFILE 'B:COMPLI.DAT' PAD;
   INPUT PRESSURE 1-8 AREA 9-19 PERAREA 20-30;   /+ mmHg,
       mm2,  +/
   PSQR=PRESSURExPRESSURE;
RUN;

GOPTIONS DEVICE=EGAL;

AXIS1 LENGTH=60 PCT LABEL=(R=0 A=90 H=0.75 CM) VALUE=(H=0.4
```

```
CM);
AXIS2 LENGTH=70 PCT LABEL=(H=0.75 CM) VALUE=(H=0.4 CM)
   ORDER=0 TO 200 BY 20;

PROC GPLOT DATA=COMPLI;
   TITLE1 H=1 CM 'COMPLIANCE CURVE';
   TITLE3 H=0.5 CM 'INCREASE IN CROSS-SECTIONAL AREA VS.
PRESSURE';
   SYMBOL1 CI=GREEN V=POINT I=NONE;
   SYMBOL2 CI=BLUE I=RQ;
   SYMBOL3 CI=NONE V=NONE I=NONE;
   LABEL PRESSURE='Pressure, mmHg'
         PERAREA='(A-Ao)/Aref, %'
         AREA='A-Ao, sqmm';
   PLOT PERAREAxPRESSURE=1
        PERAREAxPRESSURE=2 / VAXIS=AXIS1 HAXIS=AXIS2 OVERLAY;
   PLOT2 AREAxPRESSURE=3 / VAXIS=AXIS1 HAXIS=AXIS2;
RUN;

/+ PART II - PLOT SLOPE OF COMPLIANCE +/

PROC REG OUTEST=EST;
   MODEL AREA=PRESSURE PSQR;
RUN;

DATA DERIV;
SET EST;
DO P=0 TO 200 BY 200;
   DADP = (PRESSURE + 2xPSQRxP)/133.3/1000000x10xx10;
OUTPUT;
END;
RUN;

AXIS1 LENGTH=30 LABEL=(R=0 A=90 H=0.75 CM) VALUE=(H=0.4 CM);
AXIS2 LENGTH=60 LABEL=(H=0.75 CM) VALUE=(H=0.4 CM)
      ORDER=0 TO 200 BY 20;

PROC GPLOT DATA=DERIV;
   SYMBOL CI=GREEN I=JOIN V=PLUS;
```

```
   PLOT DADPxP / VAXIS=AXIS1 HAXIS=AXIS2 GRID;
   TITLE1 H=1 CM 'AREA COMPLIANCE VS. PRESSURE';
   TITLE3 H=0.5 CM 'dA/dP vs. P';
   LABEL P='Pressure, p, mmHg' DADP='Ca, m4/N (10)-10';
RUN;
```

CALC.BAS is the BASIC program that will calculate the values of compliance, incremental modulus of elasticity and pulse wave velocity from Equations 3.1, 3.6 and 3.7. The operator simply inputs the curve coefficients generated by COMPLI.SAS and the computer will output equations for the change in area, $A - A_0$ and compliance, C_A as a function of pressure, p. Then the operator inputs the pressure range to consider, Δp, the reference diameter, d_{ref}, the wall thickness, t, and the density of the fluid, ρ, and the computer will calculate C_A, E_{inc} and $\underline{c}$ in the given pressure range.

```
100 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
110 'PART I - CALCULATING AREA COMPLIANCE
120 CLEAR:CLS:KEY OFF
130 LOCATE 8,10:PRINT "CALCULATION OF AREA COMPLIANCE FROM
        QUASI-STEADY DATA"
140 LPRINT
150 LOCATE 11,20:INPUT "COEF OF P2 (10)-5 = ";C1
160 LOCATE 13,20:INPUT "COEF OF P (10)-2  = ";C2
170 LOCATE 15,20:INPUT "INTERCEPT (10)-2  = ";C3
180 CLS
190 LPRINT
200 LOCATE 10,12
210 PRINT USING "A-Ao (p) = ##.## (10)-5 p2 + ##.## (10)-2 p
        + ##.## (10)-2, mm2";C1,C2,C3
220 C4=2xC1
230 LOCATE 12,12
240 PRINT USING "  Ca (p) = ##.## (10)-5  p + ##.## (10)-2
        ,mm2/mmHg";C4,C2
```

```
250 LPRINT
260 LOCATE 15,12:INPUT "PRESSURE TO BE CONSIDERED (mmHg) = ";PRES
270 LOCATE 15,12:PRINT "                                          "
280 AREA=C1x(10^-5)x(PRES^2) + C2x(10^-2)xPRES + C3x(10^-2)
290 CA1 = (C4x(10^-5)xPRES + C2x(10^-2))x100
300 CA = CA1/133.3x(10^2)
310 LOCATE 17,12
320 PRINT USING "A-Ao (p=###mmHg) = ##.## mm2.";PRES,AREA
330 LOCATE 19,12
340 PRINT USING "Ca (p=###mmHg) = ##.## (10^-10) m4/N (##.##
        (10^-2) mm2/mmHg)";PRES, CA, CA1
350 LPRINT
360 LOCATE 22,12:INPUT "CONTINUE TO PART II";K
370 LPRINT
380 '+++++++++++++++++++++++++++++++++++++++++++++++++++++
390 'PART II - CALCULATING INCREMENTAL MODULUS
400 CLS
410 LOCATE 6,20:INPUT "LOW VALUE OF PRESSURE RANGE (mmHg) = ";LOP
420 LOCATE 8,20:INPUT "HIGH VALUE OF PRESSURE RANGE (mmHg) = ";HIP
430 LPRINT
440 LOCATE 10,20:INPUT "INTERNAL TUBE DIAMTER AT 0 mmHg (cm)= ";DIAM
450 LOCATE 12,20:INPUT "TUBE WALL THICKNESS AT 0 mmHg (mm) = ";H0
460 LOCATE 14,20:INPUT "FLUID DENSITY (@ T=18C d=0.99862 g/cc) = ";D
470 LPRINT:LPRINT
480 DENS=Dx1000                                          'DENS=kg/m3
490 H0=H0/1000                                           'H0=m
500 R0=DIAM/2/100                                        'R0=m
510 P=(HIP+LOP)/2                                        'P=mmHg
520 AA0=(C1x10^-5xP^2 + C2x10^-2xP + C3x10^-2)/10^6      'A-Ao=m2
530 A0=3.1416xR0^2                                       'A0=m2
540 A=AA0+A0                                             'A=m2
550 R=(A/3.1416)^.5                                      'R=m
560 DADP = (C4x10^-5xP + C2x10^-2)/133.3/10^6            'DADP=m4/N
570 PWV = (A0/DENS/DADP)^.5                              'PWV=m/s
580 EINC=2x3.1416xR^3/DADP/H0/10^6                       'EINC=MPa
590 CLS
600 LOCATE 11,10:PRINT USING "FOR PRESSURE CLOSE TO ### mmHg,";P
610 LOCATE 13,15
620 PRINT USING "AREA COMPLIANCE = ##.## (10)-10 m4/N";DADPx10^10
```

```
630 LOCATE 15,15:PRINT  USING "Einc = ##.## MPa ";EINC
640 LOCATE 17,15:PRINT  USING "Pulse Wave Velocity = ##.## m/s ";PWV
650 LPRINT:LPRINT
660 LPRINT "++++++++++++++++++++++++++++++++++++++++++++++++"
670 LOCATE 18,10:INPUT "ANOTHER POINT <YES>";YN$
680 IF YN$="" THEN 120
690 END
```

15 APPENDIX F: DYNAMIC INFUSION SOFTWARE

DYNAMIC is the next batch file to be executed by COLLECT. It is responsible for executing the dynamic infusion testing, storing the data and displaying it to the screen. Following DYNAMIC is the source code for the programs that DYNAMIC runs.

```
REM BATCH FILE CALLED 'A:DYNAMIC.BAT'
CLS
REM DYNAMIC COMPLIANCE TESTING ROUTINE
REM ASSUMES STATIC TESTING COMPLETE
ECHO OFF
C:\PROGLANG\BASIC\INTRPT\BASICA A:VIEW.BAS
C:\PROGLANG\BASIC\INTRPT\BASICA A:DYNCOMP.BAS
B:
C:\SAS\SAS A:VIEW.SAS
B:
C:\SAS\SAS A:DYN.SAS
ECHO ON
CLS
A:
```

VIEW.BAS is the BASIC program that collects the pressure and flow waveform data and displays the waves on the screen. Several sets of data can be collected and saved under different file names for retrival at a later time.

```
100 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
110 'DYNAMIC COMPLIANCE TESTING (called VIEW)
120 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
130 'INTRODUCTION
140 ON ERROR GOTO 1570
150 CLEAR:CLOSE:KEY OFF
160 DIM P(1000),Q(1000),PRES(1000),FLOW(1000)
170 A=100:B=150                         'a&b are DC shift
        parameters for pset
180 Y=30 : Z=45                         'amplification factors
190                                     'for voltage a= 75, b=125
200 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
210 'INTRODUCTION
220 KEY OFF:CLS:SCREEN 2
230 LOCATE 8,10:PRINT "+++ DYNAMIC COMPLIANCE TESTING ROUTINE
        +++"
240 LOCATE 11,13:PRINT "Type 1 to COLLECT NEW DATA"
250 LOCATE 13,13:PRINT "Type 2 to ENTER CONVERSION
        PARAMETERS"
260 LOCATE 16,13:PRINT "Type 9 to EXIT PROGRAM"
270 BEEP
280 A$=INKEY$
290 IF A$="1" THEN 450
300 IF A$="2" THEN 340
310 IF A$="9" THEN 1510
320 GOTO 280
330 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
340 'PARAMETER INPUT
350 CLS:SCREEN 0
360 LOCATE 4,15:PRINT "FLOW METER CONVERSION FACTORS."
370 LOCATE 2,1:PRINT "Enter linear regression results from
        SAS analysis."
380 LOCATE 6,20:INPUT "Flow Intercept Value ==>";FINTER
390 LOCATE 8,20:INPUT "Flow Slope Value ==>";FSLOPE
400 LOCATE 12,15:PRINT "PRESSURE TRANSDUCER CONVERSION
        FACTORS."
410 LOCATE 16,20:INPUT "Pressure Intercept Value ==>";PINTER
420 LOCATE 18,20:INPUT "Pressure Slope Value ==>";PSLOPE
430 LOCATE 22,10:INPUT "Enter length of arterial segment
```

```
        (cm)";LENGTH
440 GOTO 200
450 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
460 'SET UP & INITIALIZATION
470 CLS
480 LOCATE 3,10:PRINT "+++ DATA ACQUISITION SECTION +++"
490 LOCATE 5,10:PRINT "Make certain all connections are
        correct."
500 BEEP
510 LOCATE 7,10:INPUT "Are you ready to proceed with
        collection <yes>";YN$
520 IF YN$<>"" THEN 200
530 CLS
540 LOCATE 7,30:PRINT "Channel 0 = Pressure Wave"
550 LOCATE 25,30:PRINT "Channel 1 = Flow Wave"
560 LOCATE 3,25:PRINT "Real time data collection in
        progress."
570 DEF SEG = &HCFF8
580 POKE 1,6:POKE 26,0
590 J=1                                 'j=number of samples
        collected
600 T=TIMER
610 FOR N=0 TO 610                      'horizontal scrolling
620 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
630 'CHANNEL 0 (PRESSURE) DATA COLLECTION
640 POKE 10,0           'channel selection = 0  (pressure)
650 POKE 24,0
660 P(J)=(256x(PEEK(3)-240)+PEEK(2)-2047)x20/4096 'p(j) in volts
670 PSET(N,A-P(J)xY)
680 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
690 'CHANNEL 1 (FLOW) DATA COLLECTION
700 POKE 10,1            'channel selection = 1 (flow)
710 POKE 24,0
720 Q(J)=(256x(PEEK(3)-240)+PEEK(2)-2047)x20/4096 'q(j) in volts
730 PSET(N,B-Q(J)xZ)
740 J=J+1
750 NEXT
760 TOTALT=TIMER-T
770 INCT=TOTALT/N
```

```
780 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
790 'RECALL DATA DISPLAY
800 CLS
810 BEEP
820 LOCATE 8,10:PRINT "+++ Data acquisition complete +++"
830 LOCATE 10,10:INPUT "Do you wish to view (unstored) data
       <yes> ";YN$
840 IF YN$ <> "" THEN 200
850 CLS
860 LOCATE 4,20:PRINT "Recalling data..."
870 C=1
880 LOCATE 7,30:PRINT "Channel 0 = Pressure Wave"
890 LOCATE 23,30:PRINT "Channel 1 = Flow Wave"
900 FOR N=0 TO 610                    'horizontal scrolling
910 PSET(N,A-P(C)xY)
920 PSET(N,B-Q(C)xZ)
930 C=C+1
940 IF C=J THEN 960
950 NEXT
960 LOCATE 4,20:PRINT "Data Recalled    "
970 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
980 'SAVING DATA TO DISK
990 LOCATE 25,20:INPUT "Do you wish to save above data <yes>
       ";YN$
1000 IF YN$ <> "" THEN 200
1010 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
1020 'CONVERSION
1030 CLS
1040 LOCATE 10,10:PRINT "Conversion in process, please
        wait..."
1050 FOR N=0 TO 610
1060 FLOW(N)=FSLOPExQ(N)+FINTER             'flow in mm3/sec
1070 PRES(N)=PSLOPExP(N)+PINTER             'pres in mmHg
1080 NEXT N
1090 CLS
1100 '++++++++++++++++++++++++++++++++++++++++++++++++++++++
1110 LOCATE 22,20:INPUT "Enter data file name
        ('B:VIEW1.DAT')";F$
1120 CLS
```

```
1130 LOCATE 4,20:PRINT "Saving data..."
1140 OPEN F$ FOR OUTPUT AS #1
1150 C=1
1160 LOCATE 7,30:PRINT "Channel 0 = Pressure Wave"
1170 LOCATE 23,30:PRINT "Channel 1 = Flow Wave"
1180 FOR N=0 TO 610                    'horizontal scrolling
1190 PSET(N,A-P(C)xY)
1200 PSET(N,B-Q(C)xZ)
1210 PRINT #1, USING "###    ###.###    ###.###    ###.###
        ####.###   ######.###";N,INCTxN,P(C),Q(C),PRES(C),FLOW(C)
1220 C=C+1
1230 IF C=J THEN 1250
1240 NEXT
1250 CLOSE
1260 BEEP
1270 LOCATE 4,20:PRINT "Data saved to disk"
1280 LOCATE 25,20:INPUT "Do want to verify data storage <no>
        ";YN$
1290 IF YN$ = "" THEN 200
1300 '++++++++++++++++++++++++++++++++++++++++++++++++++++
1310 'DATA STORAGE VERIFICATION
1320 CLS
1330 LOCATE 2,10:PRINT "+++ DATA RETRIEVAL SECTION +++"
1340 LOCATE 4,10:INPUT "Enter data file name
        ('B:VIEW1.DAT')";F$
1350 BEEP
1360 OPEN F$ FOR INPUT AS #1
1370 LOCATE 7,30:PRINT "Channel 0 = Pressure Wave"
1380 LOCATE 23,30:PRINT "Channel 1 = Flow Wave"
1390 WHILE EOF(1) = 0
1400 INPUT #1, C, T, P(C), Q(C), PRES(C), FLOW(C)
1410 PSET(C,A-P(C))
1420 PSET(C,B-Q(C))
1430 WEND
1440 CLOSE
1450 LOCATE 4,10:PRINT "This is the data from ";F$;" being
        displayed."
1460 LOCATE 25,10:PRINT "Press 'C' to continue."
1470 BEEP
```

```
1480 A$=INKEY$
1490 IF A$="c" OR A$="C" THEN 200
1500 GOTO 1480
1510 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1520 'END OF DATA COLLECTION
1530 SCREEN 0:CLS:PRINT :PRINT
1540 BEEP:BEEP
1550 LOCATE 13,13:PRINT "Normal Termination - Program
        Complete."
1560 CLOSE:PRINT :PRINT :PRINT :SYSTEM
1570 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1580 'ERROR TRAP
1590 FOR X=1 TO 5
1600 T=TIMER
1610 CLS
1620 WHILE (TIMER-T)<1
1630 BEEP
1640 LOCATE 10,10:PRINT "ERROR TRAP ACTIVATED!!!"
1650 WEND
1660 NEXT
1670 GOTO 120
1680 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

DYNCOMP.BAS is the BASIC program that filters the waveform information from VIEW.BAS, selects a small section of wave data, reports the maximum and minimum pressures so undefined regions can be neglected (if appropriate) and the calculates the slope of the pressure wave and the dynamic compliance values along the region of wave data.

```
100 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
110 'DYNAMIC COMPLIANCE CALCULATION called 'DYNCOMP.BAS'
120 CLEAR
130 KEY OFF
140 DEFINT N
150 DIM WAVE(30),T(1000),P(1000),F(1000),TIME(500),PRES(500),
```

```
        FLOW(500),COMPLI(1000), FRACTIME(500), DPDT(500)
160 CLS
170 LOCATE 4,12
180 BEEP
190 INPUT "Enter data file name to IMPORT data
        ('B:VIEW1.DAT')";F$
200 LOCATE 8,12
210 BEEP
220 INPUT "Artery length (cm)";LENGTH
230 LENGTH=LENGTHx10                          'length in mm
240 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
250 'INPUT PRESSURE AND FLOW DATA
260 CLS
270 LOCATE 8,12:PRINT "Reading data from ";F$;", please
        wait..."
280 OPEN F$ FOR INPUT AS #1
290 WHILE EOF(1)=0
300 INPUT #1, N, T(N), Y, Z, P(N), F(N) 'y,z dummy variables
310 WEND
320 CLOSE
330 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
340 '3-POINT MOVING AVERAGE FILTER FOR PRESSURE AND 7-POINT
        FOR FLOW
350 CLS
360 LOCATE 10,12:PRINT "Filtering pressure and flow waves,
        please wait..."
370 FOR J=4 TO N-4
380 P(J)=(P(J-1)+P(J)+P(J+1))/3
390 F(J)=(F(J-3)+F(J-2)+F(J-1)+F(J)+F(J+1)+F(J+2)+F(J+3))/7
400 NEXT
410 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
420 'SELECT 3 CYCLE CHUNK FROM DATA
430 CLS
440 LOCATE 9,12:PRINT "Selecting 3 cycle chunk of data from
        ";F$
450 MAX=0:MIN=100
460 FOR J=4 TO N-4
470     IF P(J)>MAX THEN MAX=P(J)
480     IF P(J)<MIN THEN MIN=P(J)
```

```
490 NEXT
500 TH=(MAX-MIN)/2
510 R=1
520 FOR J=4 TO N-4
530     IF P(J)>TH THEN J=J+10:GOTO 530
540     IF P(J)<P(J+1) THEN J=J+10:GOTO 530
550     FOR M=J TO N-5
560         IF P(M+1)>P(M) THEN WAVE(R)=M:R=R+1:J=J+10:GOTO 580
570     NEXT M
580 NEXT J
590 C=0
600 FOR J=WAVE(5) TO WAVE(8)
610     C=C+1                          'c= # filtered pts
620     TIME(C)=T(J)
630     PRES(C)=P(J)
640     FLOW(C)=F(J)
650 NEXT
660 STRTTIME=TIME(1)
670 STOPTIME=TIME(C)
680 FOR J=1 TO C
690     FRACTIME(J)=(TIME(J)-STRTTIME)/(STOPTIME-STRTTIME)
700 NEXT J
710 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
720 'STORE PRESSURE AND FLOW TO DISK
730 CLS
740 LOCATE 11,2:INPUT "Enter file name for pressure and flow
        (B:WAVES.DAT)";H$
750 CLS
760 LOCATE 12,2:PRINT "Pressure and flow waves being stored
        to ";H$
770 OPEN H$ FOR OUTPUT AS #1
780 FOR J=1 TO C
790 PRINT #1, USING "###.###     ####.###     ######.###";
        FRACTIME(J), PRES(J), FLOW(J)
800 NEXT
810 CLOSE
820 CLS
830 LOCATE 13,2:PRINT "Wave data storage complete. Finding
        PMAX and PMIN."
```

```
840 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
850 'DETERMINE PMAX AND PMIN
860 PMAX=0:PMIN=100
870 FOR J=1 TO C
880 IF PRES(J)>PMAX THEN PMAX=PRES(J)
890 IF PRES(J)<PMIN THEN PMIN=PRES(J)
900 NEXT
910 CLS
920 LOCATE 12,10:PRINT USING "Pmax = ####.## mmHg";PMAX
930 LOCATE 14,10:PRINT USING "Pmin = ####.## mmHg";PMIN
940 '++++++++++++++++++++++++++++++++++++++++++++++++++++++++
950 'CALCULATION OF DYNAMIC VOLUME COMPLIANCE
960 LOCATE 8,10
970 BEEP
980 INPUT "Enter amplitude of PRESSURE wave to be neglected
        (i.e., 5%=5)";A
990 A=A/100
1000 CLS
1010 LOCATE 10,12
1020 PRINT "Now calculating DYNAMIC VOLUME COMPLIANCE, please
         wait..."
1030 D=1
1040 FOR B=1 TO C-1
1050 IF PRES(B)<(1+A)xPMIN OR PRES(B)>(1-A)xPMAX THEN 1210
1060       AVGQ=0:DPF=0:DPB=0:DTF=0:DTB=0:DPDTF=0:DPDTB=0:DPDT1=0:
               TEMP=0
1070       AVGQ=(FLOW(B-1)+FLOW(B)+FLOW(B+1))/3
1080       DPF=PRES(B+1)-PRES(B)
1090       DPB=PRES(B)-PRES(B-1)
1100       DTF=TIME(B+1)-TIME(B)
1110       DTB=TIME(B)-TIME(B-1)
1120       DPDTF=DPF/DTF
1130       DPDTB=DPB/DTB
1140       DPDT1=(DPDTF+DPDTB)/2
1150       IF DPDT1=0 THEN LOCATE 12,15:PRINT "DPDT1=0. Point
               skipped.":GOTO 1210
1160       TEMP=AVGQ/DPDT1/LENGTH/133.3/10^6x10^10  'm4/N (10)-10
1170       IF TEMP<-20 OR TEMP>20 THEN 1200
1180       DPDT(D)=DPDT1
```

```
1190       COMPLI(D)=TEMP
1200       D=D+1
1210 NEXT
1220 '+++++++++++++++++++++++++++++++++++++++++++++++++++++++
1230 'STORING RESULTS TO DISK
1240 CLS
1250 LOCATE 4,12
1260 BEEP
1270 INPUT "Enter data file name to EXPORT results
         ('B:DYNCOMP.DAT')";G$
1280 CLS
1290 LOCATE 6,12
1300 PRINT "Storing results to ";G$;", please wait..."
1310 OPEN G$ FOR OUTPUT AS #1
1320 FOR J=1 TO D
1330 PRINT #1, USING "#####.###  #.#### ######.###";
         COMPLI(J), FRACTIME(J),DPDT(J)
1340 NEXT
1350 CLOSE
1360 CLS
1370 LOCATE 4,12
1380 PRINT "Storage of COMPLIANCE and Pressure complete."
1390 BEEP
1400 SYSTEM
```

VIEW.SAS is the SAS program that displays the pressure and flow waves from VIEW.BAS to the screen.

```
DATA DATA1;
   INFILE 'B:VIEW1.DAT' PAD;
   INPUT TIME 8-17 PRESSURE 40-50 FLOW 51-60;
RUN;

SYMBOL1  CI=BLUE I=JOIN;

GOPTIONS DEVICE=EGAL
         NODISPLAY; RUN;
```

```
PROC GPLOT GOUT=ONE;
   AXIS1 STYLE=0
         MAJOR=NONE
         MINOR=NONE
         LABEL=NONE
         LENGTH=70 PCT
         VALUE=(' ' ' ' ' ' ' ' ' ' ' ' ' ');
   AXIS2 LENGTH=70 PCT;
   PLOT PRESSURExTIME / HAXIS=AXIS2;
   PLOT FLOWxTIME / HAXIS=AXIS1 VREF=0;
RUN;

PROC GSLIDE GOUT=ONE;
   TITLE1 'Plot of Flow and Pressure Waves vs. Time';
   TITLE3 'Figure 1.1';
RUN;

GOPTIONS DISPLAY
         DEVICE=EGAL;
RUN;

PROC GREPLAY NOFS IGOUT=ONE;
TC TEMPLATE;

TDEF P2
1/LLX=0     LLY=45
  ULX=0     ULY=90
  URX=100   URY=90
  LRX=100   LRY=45
2/LLX=0     LLY=0
  ULX=0     ULY=45
  URX=100   URY=45
  LRX=100   LRY=0
3/LLX=0     LLY=0
  ULX=0     ULY=100
  URX=100   URY=100
  LRX=100   LRY=0
;
```

```
TEMPLATE P2;

TPLAY 3:3 1:2 2:1;
RUN;
```

DYNCOMP.SAS is the SAS program that displays the slope of the pressure wave and the dynamic compliance as a function position on the wave from DYNCOMP.BAS to the screen.

```
/+  DYNAMIC VOLUME COMPLIANCE called 'DYNCOMP.SAS'  +/

LIBNAME FLOWCAL 'B:';

DATA DYNCOMP;
   INFILE 'B:DYNCOMP.DAT' PAD;
   INPUT COMPLI 1-10 FRACTIME 11-18 DPDT 19-30;
RUN;

GOPTIONS DEVICE=DMP29A4 NOCHARACTERS; RUN;

SYMBOL1 CV=GREEN V=PLUS I=JOIN;

PROC GPLOT DATA=DYNCOMP;
   AXIS1 LENGTH=70 PCT;
   PLOT DPDTxFRACTIME / HAXIS=AXIS1;
   TITLE1 H=1 CM 'Slope of Pressure Wave vs. Fractional Wave
      Time';
   TITLE3 H=0.5 CM 'Figure 1.1';
RUN;

PROC GPLOT DATA=DYNCOMP;
   AXIS1 LENGTH=70 PCT;
   PLOT COMPLIxFRACTIME / HAXIS=AXIS1;
   TITLE1 H=1 CM 'Area Compliance vs. Fractional Wave Time';
   TITLE3 H=0.5 CM 'Figure 1.2';
RUN;
```

16 APPENDIX G: CLEANSAS BATCH FILE

CLEANSAS is the batch file responsible for checking the hard drive for SAS output fragments and removing them. It is the last batch file to be executed by COLLECT.

```
CLS
REM REMOVING 'SASUSER', 'SASWORK', *.LOG AND *.LST FROM ROOT
DEL C:\SASWORK\*.*
RMDIR C:\SASWORK
DEL C:\SASUSER\*.*
RMDIR C:\SASUSER
DEL C:\*.LOG
DEL C:\*.LST
REM FILES AND DIRECTORIES REMOVED - CONTROL RETURNED TO USER
```