# Waveform Analysis of Vertebral Artery Velocity Profiles

Langer, T. [1], Bourassa, R.[2], Arnold, C.[3] & Stoneham, G. [4]

[1] Thomas Langer Ph.D., Lecturer, Dept. of Anatomy, College of Medicine, University of Saskatchewan
[2] Richard J. Bourassa, M.Sc., Clinical Professor, School of Physical Therapy, University of Saskatchewan
[3] Cathy M. Arnold, M.Sc. Assistant Professor, School of Physical Therapy, University of Saskatchewan
[4] Grant Stoneham, MD., Assistant Professor, Dept. of Medical Imaging, College of Medicine, University of Saskatchewan

Address correspondence to:

T. Langer
Department of Anatomy and Cell Biology
Health Sciences Building
University of Saskatchewan
Saskatoon, Sask.
S7N 0W3
e-mail: tlanger@sk.sympatico.ca
phone: 306-249-3236

## Introduction

This paper addresses three questions relative to the velocity waveforms measured in the vertebral arteries during vertebral artery stress tests. They all relate to the general characteristics of the measured parameters, rather than the response of the vertebral arteries to the stress tests.

The first question is whether the characteristics of the blood flow change as a consequence of the testing itself. It is possible that mobilizing the neck into endrange positions brings about a sustained overall increase or decrease of blood flow. Since there are often substantial differences in the blood flow parameters for the two vertebral arteries in the same individual and between individuals, it is necessary to normalize the test flow parameters to the rest or neutral position values in that artery in that individual. If the resting value is shifting systematically throughout the testing session, then normalizing may lead to a false impression of changes in response to the stress positions where the changes are in response to other aspects of the testing. The tests were always done in the same order, so, if there were a consistent increase in a parameter in neutral position as the testing progressed, then the values on the final tests would be elevated compared to the values in the early tests, simply because the baseline shifted. To check for systematic trends between tests, the parameters of blood flow were measured in neutral position prior to testing and, again, after testing, The result in these two tests are compared in the first section of the Results.

When measuring flow in the vertebral arteries with duplex doppler ultrasound, the measured flow parameters are velocities. In particular, two measurements are collected, the peak systolic velocity (**S**) and the end diastolic velocity (**D**). These measurements are taken at two extreme points in the pulse cycle. Peak systolic velocity is the maximal velocity and end diastolic velocity is the velocity at the end of the diastolic phase, just before the velocity begins to climb for the next pulse cycle. It is logical to ask how well these two extreme values capture the entire waveform, which may be quite complex and which varies substantially from test position to test position (Figure 1). Beyond that, one might wonder how well these measurements of velocity capture the volume of blood flow through the vessels. Addressing those concerns is a major part of this paper.

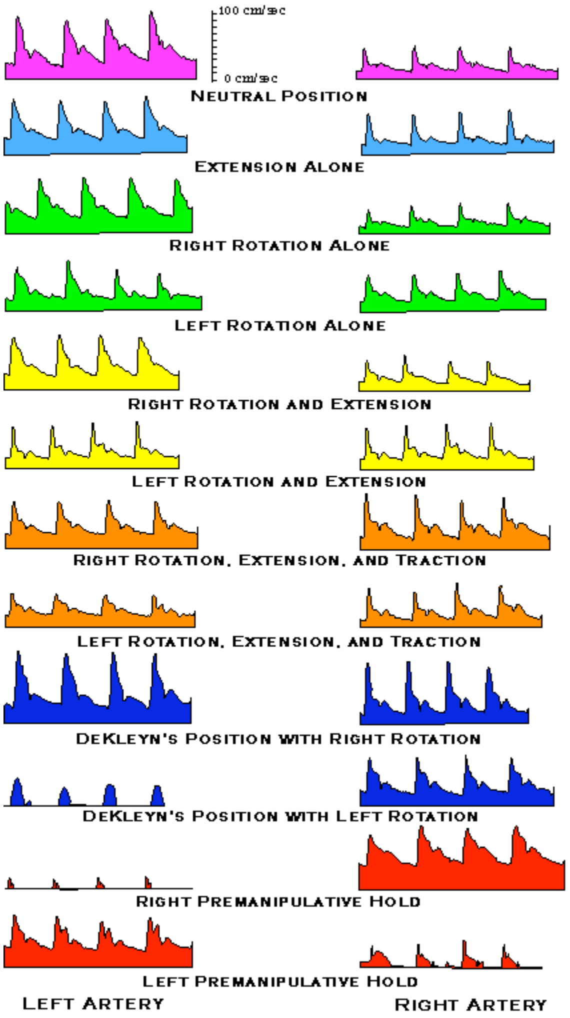

**Figure 1. The waveforms for all stress tests during a single testing session in a single subject.** The pulse blood flow velocity waveforms have been traced for each sample collected in a single testing session of a single test subject. The subject was about average in her response to the stress positions. Note the differences between the two arteries in neutral position, which carries through to the other test positions, but does not necessarily predict the strength of the response to all the strains.

A third question arises from the examination of the data on blood flow. It is possible that there are statistical relationships between the measured parameters independent of the particular test being done. Such relationships may provide some insight into the control of the blood flow and how it might be changed by movements in the neck. The third part of the Results addresses those points.

## Methods

The analysis in this paper is based upon the same data as in the paper describing the response of vertebral artery blood flow to a variety of head and neck configurations that are thought to stress the vertebral artery (Arnold, et al., 2004). The collection and processing of the data was identical to that described in that paper, except that the profiles used here were taken directly from the x-ray film used to record the duplex doppler ultrasound. The profiles were entered into the computer with a scanner and traced in Canvas 6 as separate layers from the waveform image. The areas and heights of the traced regions were automatically calculated as attributes of the tracing objects. These values were copied into *Microsoft Excel* for tabulation and simple data manipulation. The plots were created in *CA-Cricket Graph III*.

## Results

*Doppler Ultrasound Responses in Neutral Position*

In neutral position there is presumably minimal stress upon the vertebral arteries, therefore the behavior of blood velocity in neutral gives a baseline with which to compare the responses during the stress tests. The means and standard deviations of the measured variables are as given in Table 1 for 22 test subjects. The statistics for the right and left arteries, individually, are consistent with their being statistically equivalent. This is relevant because the values for the two arteries in individual subjects may be quite different. Sometimes this is clearly due to narrowing of one of the arteries and sometimes the cause is not known.

To assess the normal variability in blood flow within individual subjects we compared the values of the parameters in neutral position prior to testing with the values after testing. These comparisons also gave us the limits for detecting changes in blood flow in response to the test positions. The percent difference between the flow parameters prior to testing and after testing was computed for each subject (Table 1, Figure 2). The values for percent change in the right and left arteries are consistent with their being statistically equivalent. All the measurements in neutral position are consistent with there being no change with re-testing and no correlation between the values obtained in two separate tests.

**Table 1. The averages and variation of peak systolic velocity (S), end diastolic velocity (D) and resistive index (R) in neutral**

| | Response Indices | | | | Changes in Response Indices | | | |
|---|---|---|---|---|---|---|---|---|
| | **S** | **D** | **R** | **S/D** | **%S** | **%D** | **%R** | |
| **BOTH** | 57.62 | 18.25 | 0.68 | 3.28 | 4.62 | 2.76 | 2.26 | *Average* |
| **Arteries** | 14.07 | 5.00 | 0.07 | 0.76 | 18.41 | 26.83 | 10.25 | *SD* |
| **RIGHT** | 56.63 | 17.82 | 0.68 | 3.31 | 3.35 | -3.14 | 4.51 | *Average* |
| **Artery** | 13.40 | 5.06 | 0.07 | 0.78 | 15.66 | 24.30 | 12.54 | *SD* |
| **LEFT** | 58.60 | 18.68 | 0.68 | 3.24 | 5.88 | 8.67 | 0.02 | *Average* |
| **Artery** | 14.79 | 4.95 | 0.06 | 0.76 | 21.11 | 28.47 | 6.89 | *SD* |

**Table 1. The blood velocity parameters for all samples taken in neutral position.** There is no significant difference in the average values for the right and left arteries. There is also a comparatively large variation in the parameters.

## Waveform Analysis

Doppler ultrasound measures blood velocity in a narrow cylinder approximately aligned with the longitudinal axis of the blood vessel and centered in the cross-section of the vessel. What we actually wish to study is the volume of blood flow. Therefore, the first area to be addressed is the relationship between the velocity of blood flow and the volume of blood flow.

It is straightforward to show that there is a uniform distribution of volume *versus* velocity in a tube with laminar flow. That is, if the maximal velocity is 100 cm/sec, then 1/100th of the blood in the tube is moving at 1 cm/sec, 1/100th at 2cm/sec, 1/100th at 3 cm/sec, and so on, up 100 cm/sec. Consequently, the average velocity of the blood is half the maximal velocity. When measuring the blood velocity with doppler ultrasound, the technician attempts to obtain the waveform with the maximal amplitude, therefore the measured parameters are estimates of maximal blood velocity. Given a circular vessel of unchanging caliber, the velocity is a good estimate of blood flow volume. The way in which the measurements were taken, at mid-cervical levels of the vertebral artery, the vessel caliber was not strongly perturbed by the positioning of the neck. Therefore, the measured velocity should be a reasonable estimate of the average velocity in the vessel and, consequently, of the rate of flow.

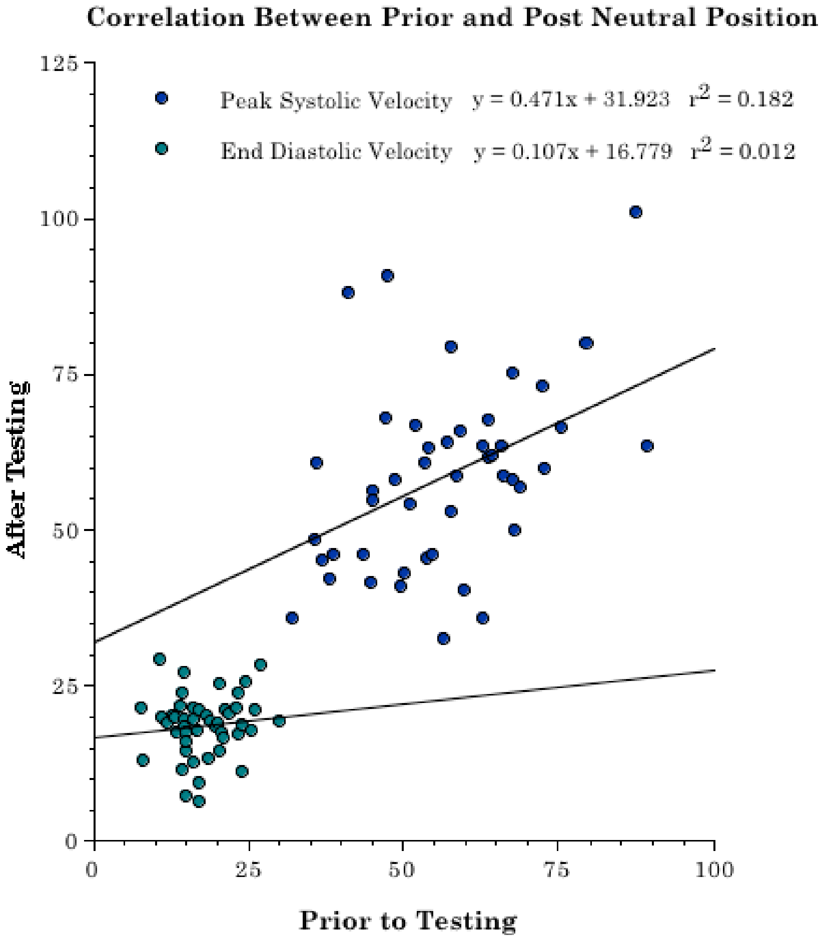

**Figure 2. The distributions of peak systolic velocity and end diastolic velocity prior to the testing to after the testing.** There is minimal correlation between the values before and after testing.

## Waveform Analysis

Doppler ultrasound measures blood velocity in a narrow cylinder approximately aligned with the longitudinal axis of the blood vessel and centered in the cross-section of the vessel. What we actually wish to study is the volume of blood flow. Therefore, the first area to be addressed is the relationship between the velocity of blood flow and the volume of blood flow.

It is straightforward to show that there is a uniform distribution of volume *versus* velocity in a tube with laminar flow. That is, if the maximal velocity is 100 cm/sec, then 1/100th of the blood in the tube is moving at 1 cm/sec, 1/100th at 2cm/sec, 1/100th at 3 cm/sec, and so on, up 100 cm/sec. Consequently, the average velocity of the blood is half the maximal velocity. When measuring the blood velocity with doppler ultrasound, the technician attempts to obtain the waveform with the maximal amplitude, therefore the measured parameters are estimates of maximal blood velocity. Given a circular vessel of unchanging caliber, the velocity is a good estimate of blood flow volume. The way in which the measurements were taken, at mid-cervical levels of the vertebral artery, the vessel caliber was not strongly perturbed by the positioning of the neck. Therefore, the measured velocity should be a reasonable estimate of the average velocity in the vessel and, consequently, of the rate of flow.

The second part of this question concerns the validity of the measurements of velocity. If we measured the velocity continually and then multiplied by the vessel cross-sectional area, then we would obtain a moment to moment measurement of the volume of flow. To assess the volume of flow during a pulse cycle, we would only have to add up the flow in all those moments during a pulse cycle. However, it was not practical to quantitatively measure the velocity many times during the pulse cycle. Instead, the velocity was estimated by two indices; the maximal velocity during the systolic phase of the pulse and the velocity at the end of the diastolic phase. One might reasonably ask how well those two numbers, collected at two extreme points of the pulse cycle, characterize the volume of flow during a pulse cycle. In addition, the indices were measured for only a single pulse, therefore one might ask how consistent the waveform was for multiple cycles. This section examines these queries.

The doppler ultrasound waveform for blood flow through the vertebral artery at mid-cervical levels is characterized by two components (Figures 1 and 3). These may be roughly divided into a pulsatile transient that rises quickly in the early part of the systole and then falls more slowly, but still comparatively quickly through the remainder of the systole. As it declines, it often has a hump, where it plateaus or falls substantially less quickly for awhile. Sometimes the hump will become more prominent and even form a second peak during systole. It is not uncommon to observe a quick precipitous drop at the end of systole and then a quick transition into a second, low, slow transient that rises only a fraction of the distance of the systolic transient and then slowly falls towards a constant diastolic flow. The relative proportions of the various components varied from test to test and from subject to subject, but most of the components are present in all the test positions in all of the subjects. Figure1 shows all of the waveforms for all of the test positions in a single subject, who was about average in her response to the stress tests.

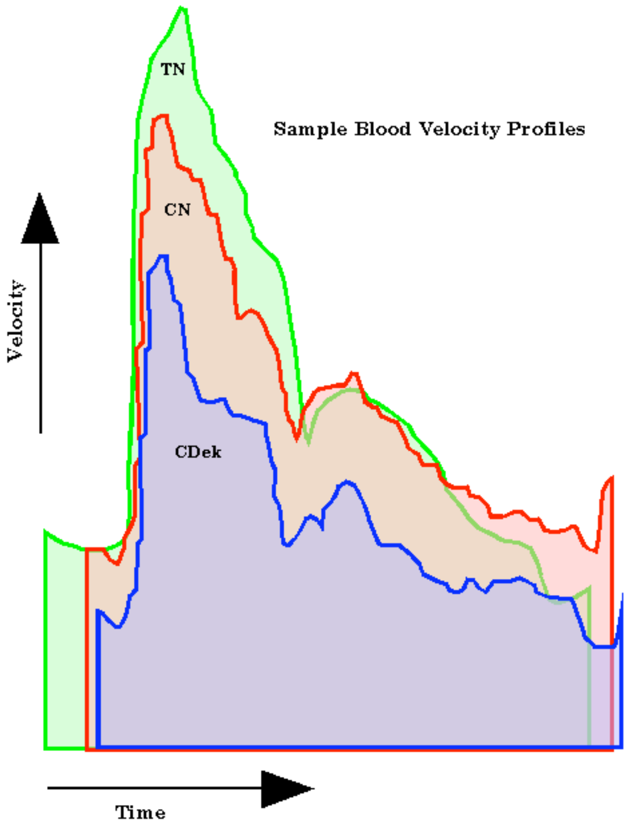

**Figure 3. Three representative velocity profiles collected in neutral (TN and CN) and DeKleyn's Position (Cdek).** As with most pulse cycles the velocity profiles have an initial transient pulse during systole and a gradually declining velocity during diastole. Usually, there is a brief transient drop in velocity between the two phases.

Usually, when studying the response to stress, we did not deal with the details of the waveform, but abstracted it as two measurements. The first is the maximum velocity during the systolic pulse, called the **peak systolic velocity (S)** and the second is the blood velocity near the end of diastole, usually the minimal velocity during the pulse cycle, the **end diastolic velocity (D)**. Two additional indices were computed from these measurements; the ratio of the peak systolic velocity to the end diastolic velocity, **S/D**, and the resistive index, **R**. The resistive index is the proportion of the peak systolic velocity that is in the pulsatile part of the flow.

$$\mathbf{R} = \frac{(\mathbf{S}-\mathbf{D})}{\mathbf{S}}$$

We did not analyze the ratio of the systolic and diastolic velocities. The resistive index has been studied in some depth, since it is commonly thought to be related to the amount of resistance distal to the site of the measurements.

*Baseline and pulse flow:*

An alternative way to view the pulse cycle may be as a combination of a roughly constant, baseline, flow which may be estimated by the end diastolic velocity and a superimposed pulsatile flow that is to some degree a function of the magnitude of the peak systolic velocity minus the end diastolic velocity, a quantity that will called the **pulse amplitude, P**.

The quantity of blood that flows through the artery depends strongly upon the baseline velocity, because that flow is approximately constant and it extends throughout the pulse cycle. The baseline steady flow is proportional to the baseline velocity multiplied by the arterial cross-section and the pulse duration.

An equally large pulse amplitude would result in a much smaller amount of blood flow, because the pulse is narrow and concave upwards. If the pulse amplitude were twice the baseline amplitude, then the amount of additional blood flow in the pulse would still be less than that in the baseline flow. In many waveforms the pulse drops to a velocity near baseline well before systole is over, so the pulsatile flow may be a small fraction of the baseline flow.

*Static versus dynamic parameters:*

The baseline flow depends more upon the overall static restriction to flow, therefore it is a static parameter of the vessel resistance (see Discussion). On the other hand, the pulsatile part of the cycle is more dependent upon a transient storage and a dissipation of the increased pressure, therefore it is a dynamic parameter of the vessel resistance. Consequently, we might expect these two parameters to behave somewhat differently with constriction of the vessel. In fact, that is what is observed when we place the head and neck in a variety of different test positions (Figure 1).

Rather than the pulse amplitude, the ratio of the pulse amplitude to the peak systolic velocity, the resistive index, was generally taken as a measurement of the interplay between the static and dynamic components of the resistance to blood flow. Dividing by the peak systolic velocity yields a parameter that varies from 0.0, when there is no resistance to flow, to 1.0, when the vessel resistance is sufficient to stop flow completely during diastole. It has no meaning when there is no blood flow. When the resistive index is low, most of the flow is in the baseline flow, and when it is high, most of the flow is in the pulsatile component.

## Relations Between Steady Flow and Pulsatile Flow

It is straightforward to measure the steady flow and pulsatile flow for recorded waveforms. The areas subtended by the two may be determined by numerically integrating the areas enclosed by polygons that trace the wave elements. This has been done for every test in three subjects. The types of relationships between the volumes of flow and the flow velocities are illustrated in Figure 4, which is taken from an average subject. The results for all three subjects are as follows.

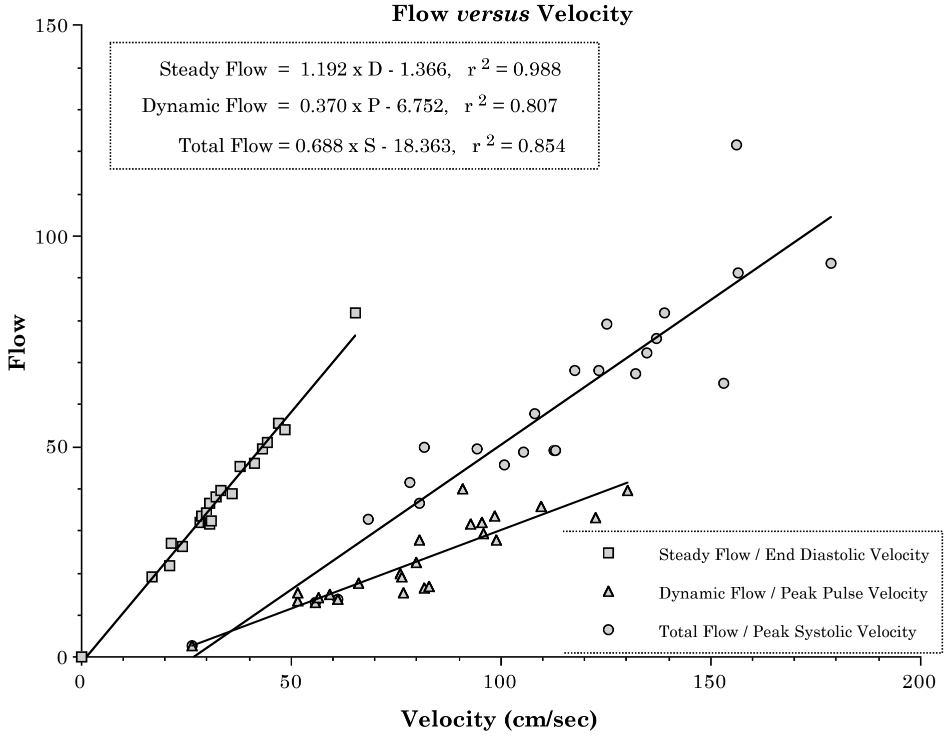

**Figure 4. The relationships between the measures of blood velocity and the baseline and pulsatile flows in a single subject.** The measured areas of the baseline and pulsatile components of a set of the ultrasound tracings were computed for each test in a single test session performed with a subject that responded to an average degree. In each pulse tracing the peak systolic and end diastolic velocities were also measured. The volume flows were plotted against the velocities. There were good correlations between the velocities and flows, indicating that the two measurements of blood velocity give a good indication of the blood flows in the vertebral arteries.

The steady flow is very well correlated with the end diastolic velocity ($r^2 = 0.988$, 0.997, and 0.949), which is not suprising since the main unmeasured parameter is the pulse duration and the each subject's pulse rate remained steady during the test sequence.

The relation between the pulse height and the pulsatile flow is substantially more variable, but still remarkably consistent, given the wide variation in the shape of the pulse from test to test and even within a particular test. The correlation coefficients were $r^2 = 0.725$, 0.814, and 0.807 for the three subjects. The correlations between the peak systolic velocity and the total pulse flow were also quite good; $r^2 = 0.854$, 0.777, and 0.910. All these observations indicate that the velocity measurements are good indicators of the volumes of the flows.

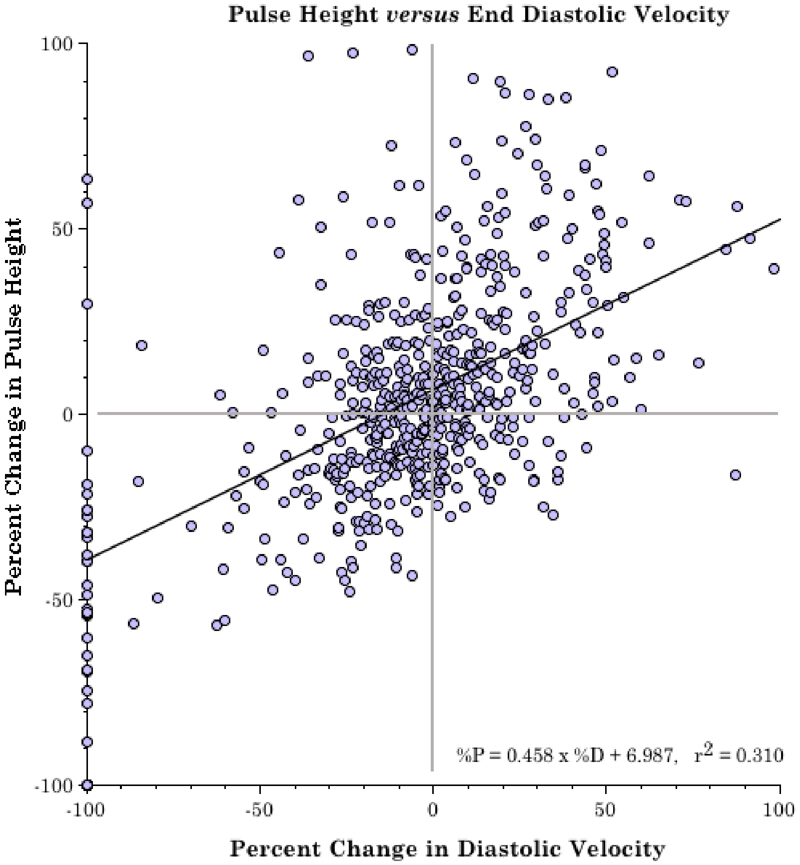

**Figure 5. There is very little correlation between diastolic velocity and pulse height**.

It came as something of a surprise to find that there is poor, approximately 0.3, correlation between the amount of flow in the pulse and the amount of flow in the steady baseline flow in the individual subjects (Figure 5). This is also found to be the case for all the tested subjects, when we used the end diastolic velocity and the pulse height as substitutes for the steady and pulsatile flow measurements.

If we sort the data by test position, then some tests show a moderate correlation between the steady and pulsatile flows, in particular, the premanipulative holds and some of the rotations. The critical factor seems to be the saturation of the response in some subjects. When there were tests in which some subjects had the cessation of blood flow for a part of the cycle, then there is a moderate correlation. When all the responses were similar to the flow in neutral position, then there was no correlation between the pulse amplitude and the magnitude of the steady flow.

The consensus of these observations is that, normally, there is little correlation between the magnitude of the pulsatile flow and the magnitude of the steady flow, but the total flow remains approximately constant for a given test position. How the flow is apportioned between the two components is variable from individual to individual and test to test and there are no apparent rules that apply across subjects or tests.

## General Attributes of the Total Population

### *The relationship between peak systolic velocity and end diastolic velocity*

This and the next section examine the relationships between the diastolic velocity and the peak systolic velocity. Remember that these are good approximations to the baseline steady flow and the total flow, respectively.

There is a moderate correlation between the value of the end diastolic velocity and the peak systolic velocity for the same test. The relationship is $\mathbf{D} = 0.287 * \mathbf{S} + 0.430$, with a $r^2 = 0.600$ (Figure 6). The constant, 0.430, is essentially zero in a range that extends to more than 50 cm/sec. Therefore, the diastolic velocity is approximately 28% of the systolic velocity, on average. However, for peak systolic velocities below about 40 cm/sec, the end diastolic velocity is often at or near zero.

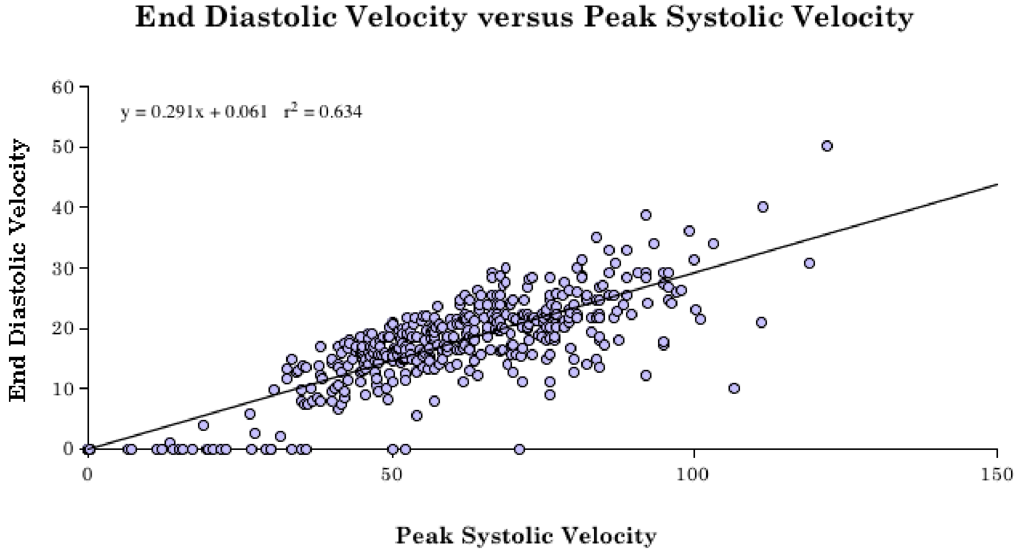

**Figure 6. End diastolic velocity is moderately correlated with peak systolic velocity.** Comparing all the measurements taken during stress tests and in neutral position, there is a ratio of about 0.3 between the end diastolic velocity and the peak systolic velocity. However, there are tests in which occlusion of the vessel distal to the point of measurement causes the cessation of blood flow during diastole.

*The relationship between the percent changes in peak systolic velocity and end diastolic velocity*

There is a moderately good correlation between the change in peak systolic velocity and the change in end diastolic velocity in the same test (Figure 7). The relationship is given by the equation.

$$\mathbf{\%D} = 1.055 * \mathbf{\%S} - 7.191\%, r^2 = 0.615.$$

The additive term is very small compared with the range of end diastolic velocities, which range from −100% to about +350%. Therefore, the relationship between the average changes in the systolic and diastolic velocities is also a constant ratio, very nearly unity.

# Discussion

*Flow Velocity in Neutral Does not Change Systematically With Testing*

The evidence from comparing flow prior to testing to flow after testing indicates that there was, on average, no change. This statement should not be confused with the statement that blood flow was the same after testing as it was before. Examination of even a few subjects will reveal that there could be substantial differences between the two waveforms in a single individual. There was considerable variation in the flow parameters upon re-testing, but the probability of a parameter increasing a certain amount was the same as the probability of it decreasing the same amount. Consequently, there does not appear to have been any systematic change in baseline flow.

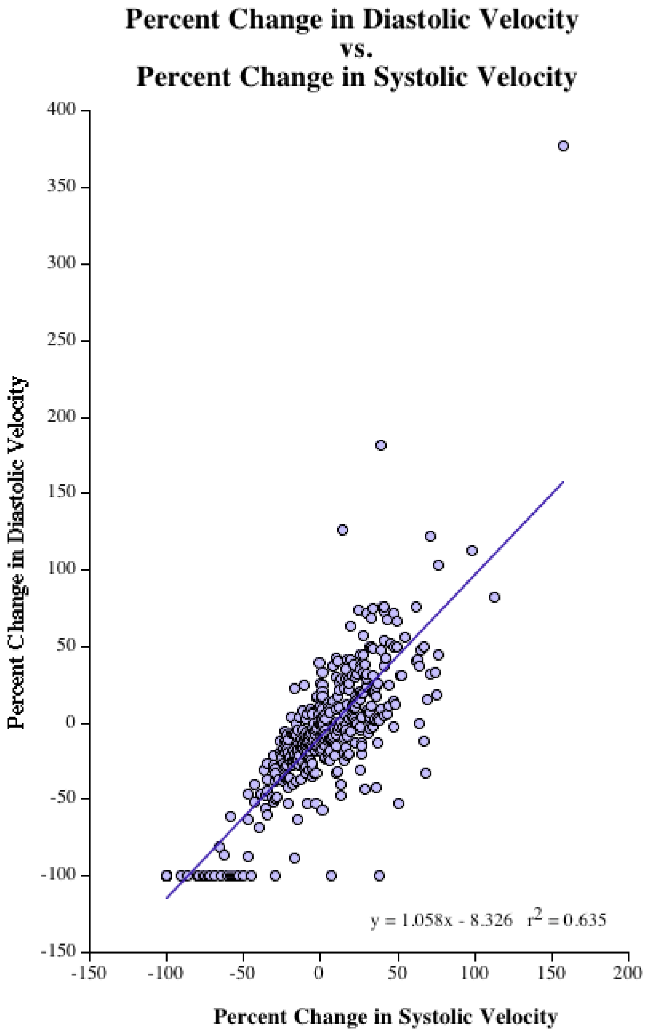

**Figure 7. End diastolic velocity is moderately correlated with peak systolic velocity.** Comparing all the measurements taken during stress tests and in neutral position, there is a ratio of about 1.0 between the percent change in end diastolic velocity and the percent change in peak systolic velocity. However, there are tests in which occlusion of the vessel distal to the point of measurement causes the cessation of blood flow during diastole, therefore the percent change in diastolic velocity is 100%.

The substantial variation in blood flow in the absence of strain in the vertebral arteries places restraints on the degree to which one can detect changes due to strains. It takes a substantial change that is consistent from test subject to test subject in order to have a detectable effect.

*The dependence of blood velocity upon vessel resistance:*

If we view the resistance to flow as being like an electrical impedance, then the baseline steady velocity is more a reflection of the passive resistance component of the impedance and the pulse amplitude is more a reflection of the inductance or transient storage component. Two principal factors change resistance to flow. Constriction of the vessel will decrease the rate of flow by reducing the cross-sectional area. The flow volume is proportional to the fourth power of the radius, therefore small changes in vessel diameter can produce large changes in flow. However, in an elastic vessel, the diameter of the vessel is modified by the pressure of the fluid within the vessel and energy may be dynamically stored in the vessel wall. This interplay between the elastic vessel and the fluid that it contains may lead to some interesting consequences for the parameters of blood flow that we measure. However, the interplay between these factors is subtle enough that it is impossible to predict *a priori* the actual behaviour.

*Flow with reduced resistance:*

If the resistance to flow is reduced, we would expect there to be greater baseline velocity, because more of the pressure difference through the system occurs in the monitored segment, the caliber of the vessel remains nearly the same, and, with less resistance to flow, the quantity of flow will increase, leading to faster flow. On the other hand, with low resistance, any increase in pressure at the origin of the system will be rapidly dispersed by fluid flow and little stretching of the vessels will occur, so we might expect the pulse amplitude to be reduced. In other words, more of the flow will be steady flow and less will occur as pulsatile flow.

The extreme of this situation might be a nearly frictionless fluid in which any increase is pressure causes an immediate, proportionate increase in blood flow so the pressure is dissipated before it can build to any appreciable extent. If pressure remains nearly the same, then velocity remains nearly the same.

*Flow with increased resistance:*

The situation that we are more interested in is the opposite change in which there is a narrowing of the vessel distal to the point of measurement and a consequent increase in resistance, which will slow flow through the system overall, because the narrowing of the vessel will reduce the maximal flow through the constriction. This constriction and consequent decrease in flow will be reflected in the decline of the baseline flow velocity. However, since there is a resistance to flow it is possible to build up more pressure prior to the narrowing, because the increased flow produced by the pulse is not as readily dissipated. There will be a small amount of transient storage of fluid prior to the constriction, possibly due to dilation of the vessel. The increased pressure will tend to drive the blood more quickly through the constriction. The consequence is going to be greater peak systolic velocity, but less total flow, because the decline in baseline flow will be greater than the increase in pulsatile flow.

This increase in pulse velocity is going to occur only for comparatively small amounts of constriction, because the increased resistance will overwhelm the pulse pressure and restrict flow. The consequence of small constrictions of the artery may be increased pulse velocity and decreased baseline velocity. However, we expect that continuing to increase the constriction will cause a decrease in both velocities until the baseline pressure is not sufficient to push blood through the constriction, but there is sufficient pressure to temporarily over-ride it during the pulse. In that situation, we would see blood flow only during the systolic phase of the pulse cycle. Finally, with more constriction, even the pulse pressure will not be sufficient to push blood through the constriction and there will be no blood flow during the pulse cycle.

*Validity of peak systolic velocity and end diastolic velocity as indices of vertebral artery blood flow.*

It is rather suprising how good an indication of blood flow the two extreme parameters turned out to be. Given the wide variation in pulse profiles that one sees when examining a number of stress tests, the measurement of height turns out to be reasonable indicator of area. This greatly simplifies the analysis of blood flow in response to neck configuration, in that we can substitute two individual measurements for an integral of the signal.

### *Correlations between velocity parameters*

The modest correlation between the peak systolic velocity and diastolic velocity and between the change in those parameters indicates that there is an underlying mechanism that is regulating blood flow. As indicated above, there is a possibility of a complex relationship, that depends on the amount of resistance and the elasticity of the vessel walls. We see something of that non-linearity in the saturation that occurs with occulsion. However, the relationships between the parameters does extend sown into the range where we see occlusion in some tests. The situation is almost much more complicated that these averaged views would seem to indicate. If one wants to study these relations in detail it would be necessary to examine a number of vessels that are subjected to partial occulsion is a much lore controlled manner than what occurred in these measurements.