Effect of Temperature on Pulse Wave Velocity and Arterial Compliance

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The compliance of a material is the ability of the material to expand or contract. A low arterial compliance will lead to high blood pressure and, ultimately, cardiovascular disease. The velocity of the pulse wave traveling through an artery is a function of the compliance of the artery that it is traveling through. Therefore, the compliance of an artery can be indirectly observed by measuring several pulse wave velocities in the artery. This experiment investigates the effect, if any, of temperature on arterial compliance. Two electrocardiographs (ECGs) were taken from healthy human subjects at the right wrist to right elbow, before and after an application of a temperature gradient. For one study, the subject's arm was put into water of a significantly higher temperature than the body. For the other study, the subject's arm was put into water of a significantly lower temperature than the body. From the ECGs taken, the relative pulse wave velocities before and after the applications of the local temperature gradients were determined. It was determined that the local heating resulted in an increase in the pulse wave velocity in the artery, and the application of the local cooling resulted in a decrease in the pulse wave velocity in the artery.

Keywords: compliance, pulse wave velocity, cardiovascular, thermoregulation

1. Background and Introduction

According to estimates taken in 2006, over 81.1 million people in the United States suffer from at least one form of cardiovascular disease. Of these people, 76.4 million of them have high blood pressure[1]. One of the underlying sources of high blood pressure, and of many cardiovascular diseases as well, is low arterial compliance[2]. The compliance of a blood vessel is defined as the ability of the vessel to expand, or contract, to best accommodate a particular volume and a particular hydrostatic pressure of blood[3]. In more general terms, arterial compliance is the elasticity of an artery. One way to observe arterial compliance is by observing the velocity of the pulse wave moving through an artery. The pulse wave is the increase of pressure radiating through the arteries that occurs with each contraction of the left ventricle of the heart[4]. Because the pulse wave velocity is a function of arterial compliance, a relative arterial compliance can be determined by recording several pulse wave velocities through that artery. This allows one to identify individuals who have a low arterial compliance and are susceptible to

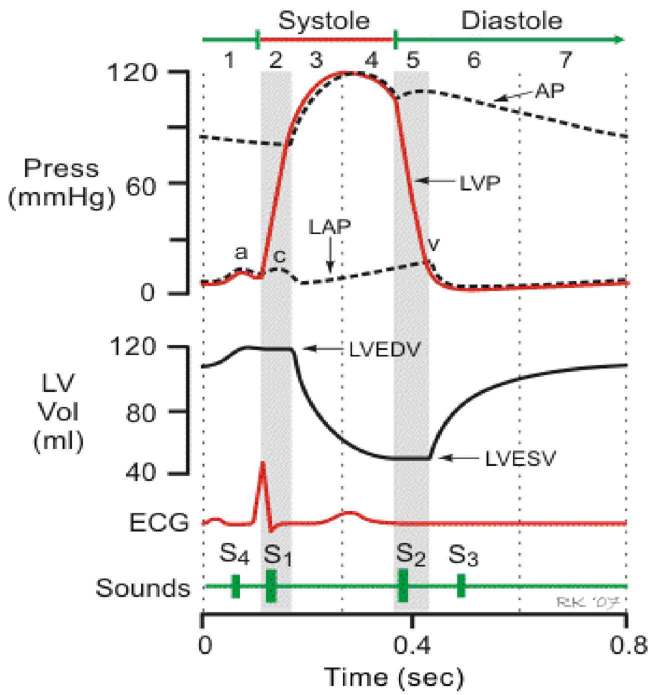

Figure 1. Changes in pressure (P) and volume (V) of left ventricle (LV, solid lines) and aorta (LA, dotted lines) during cardiac cycle[6]. The left ventricle's volume varies between its end-diastolic volume (EDV) to its end-systolic volume (ESV) during one cycle.

hypertension and other cardiovascular diseases.

The cardiovascular system is made up of two parts, the pulmonary circulation portion and the systemic circulation portion. This experiment focuses on the systemic portion of the cardiovascular cycle. The systemic portion circulates oxygen-rich blood throughout the body. It does this by transferring the oxygenated blood in the left atrium to the left ventricle, where the blood is then pumped through the aorta into systemic arteries. The blood is pumped into these arteries by the contraction of the left ventricle[5]. This phase of the cardiac cycle, known as systole, increases the pressure inside the ventricle, which ejects the blood through the aorta to the lower pressure arteries. The blood flow is driven through the arteries by this transient movement of pressure called the pulse wave. When all of the blood is ejected from the left ventricle, the aortic valve closes, and the systolic phase of the cardiac cycle ends. The left ventricle is then refilled with oxygenated blood from the left atrium, lowering its pressure in the process. This phase of the cardiac cycle, characterized by low blood pressure, is known as the diastole[6]. The change in volume and pressure of the left ventricle during the cardiac cycle can be seen in Figure 1.

During the pulse wave's travel through the systemic arteries, it will encounter a pulse wave reflective site at some point. An example of one of these sites is a major branching point such as the renal artery and femoral artery junction. After encountering this reflective site, the pulse wave is reflected in the opposite direction so that it returns to the heart. Under normal circumstances, the pulse wave returns to the heart after the aorta has closed[7]. This is during the diastolic phase of the cardiac cycle, so diastolic pressure is increased. Because of constructive interference, the magnitude of the diastole is thus increased[8]. However, the pulse wave may return to the heart before the aorta has closed, during the systolic phase of the cardiac cycle[7]. This increases systolic pressure and consequently increases the magnitude of the systole.

The timing of the return of this pulse wave to the heart is determined by the pulse wave's velocity, which is a function of arterial compliance[8]. This pulse wave velocity (PWV) can be determined by dividing the distance traveled in an artery (Δx) by the time it takes for the wave to travel that distance, or the pulse transit time (PTT)[9].

$$PWV = \frac{\Delta x}{PTT} \quad (1)$$

The pulse wave velocity can also be calculated by using Eq. (2), the Bramwell-Hill equation, which relates the pulse wave velocity to pressure and volume of the artery. It does this using the change in pressure of the artery (ΔP), the volume (V) and change of volume of the artery (ΔV), and the density of the blood (ρ)[9].

$$PWV = \sqrt{\frac{V \cdot \Delta P}{\rho \cdot \Delta V}} \quad (2)$$

The speed at which the wave travels in the arteries is heavily based on the elasticity of the arteries[8]. Arterial compliance (C) is the change in arterial blood volume (ΔV) due to a given change in arterial blood pressure (ΔP)[10].

$$C = \frac{\Delta V}{\Delta P} \quad (3)$$

Eq. (3) can be inserted into Eq. (2), showing that the pulse wave velocity and the square root of the compliance of an artery are inversely related[10].

$$PWV = \sqrt{\frac{V}{\rho \cdot C}} \quad (4)$$

An artery with a high compliance will stretch out to allow the pulse wave to pass. This stretching of the artery causes the pulse wave to travel slower than it would without the stretching. In contrast, an artery with low compliance and high arterial stiffness will not stretch out when the pulse wave passes. Therefore, because the square root of arterial compliance and pulse wave velocity are inversely related, the pulse wave will travel faster through arteries with a low compliance[8]. At optimum performance, the arteries' compliance will allow the pulse wave to return to the heart at such a time that diastolic pressure will increase. However, a relatively low compliance will make the pulse wave travel faster and return to the heart more quickly. The pulse wave will return during the systolic phase of the cardiac cycle, increasing the systolic pressure[7]. This will result in higher cardiac work for this low arterial compliance. This indicates that a high arterial compliance is much more beneficial than a low arterial compliance[11].

Much research has already been done studying the effect of factors on long-term behavior of arterial compliance. A well-known factor affecting arterial compliance is aging. Studies have shown that as an individual gets older, arteries lose their compliance and become much stiffer. With this stiffening, the arteries lose their ability to distend in a response to increased pressure. This leads to an increased blood pressure as individuals age, resulting in an eventual increase in cardiovascular risk[12]. The stiffening of the arteries can be attributed to the increase in the number of collagen fibers surrounding the arteries in elder individuals. Collagen fibers lose their elasticity as age increases and stiffen up around the arteries. This hinders the arteries' ability to distend when needed[13].

Another factor affecting arterial compliance that has been extensively studied is physical exercise. In a study done determining the effect of physical activity on arterial compliance, Tanaka and colleagues found that aerobic exercise training can prevent the stiffening of arteries[13]. The study showed that this regular physical exercise could not increase arterial compliance, but it would slow the normal loss of compliance developed from aging[12].

2. Theory

This experiment seeks to observe the effect of temperature on pulse wave velocities, indirectly determining its effect, if any, on arterial compliance. Extensive previous research has been done investigating the effect of temperature on the human body and its thermoregulation that would suggest that an increase in the temperature of the body will cause an increase in arterial cross-section in that area of the body[14]. The human body has an extensive positive/negative feedback system that allows it to regulate its body temperature[15]. In all warm-blooded animals, including humans, vasodilation occurs in response to an increase in the temperature of the ambient environment[6]. Vasodilation is increase in the internal diameter of a blood vessel that results from relaxation of smooth muscle within the wall of the vessel, thus causing an increase in blood flow[16]. This vasodilation occurs in an effort to divert the flow of heated blood to the surface of the skin. The vasodilation is a function of homeostasis and will lead to a decrease in the temperature of the surface of the body[6].

Using the Bramwell-Hill equation, Eq. (4), the pulse wave velocity can be calculated in terms of the volume of an artery (V), the compliance of the artery (C), and the density of the blood flowing through the artery (ρ). The volume of the artery can be replaced by the cross-sectional area of the artery (A) to obtain a pulse wave velocity factor (PWV factor)[17].

$$PWV\ factor = \sqrt{\frac{A}{\rho \cdot C}} \tag{5}$$

An increase in temperature should increase the diameter of an artery which would, consequently, increase the cross-sectional area of the artery. Likewise, a decrease in temperature should decrease the diameter of an artery. This would decrease the cross-sectional area of the artery.

The pulse wave velocity can also be calculated in terms of the distance traveled by the pulse wave (Δx) and the pulse transit time (PTT), as defined in Eq. (1). A new equation can be obtained by rearranging Eq. (1) to solve for the distance traveled by the pulse wave (Δx).

$$\Delta x = PWV \cdot PTT \tag{6}$$

We can use this equation together with Eq. (5) to eliminate the distance traveled by the pulse wave. We assume no change in the arterial length as a consequence of the applied temperature gradient; further study to support such an assumption is encouraged. We are now able to compare the cross sectional area (A_i), arterial compliance (C_i), and pulse transit time (PTT_i) before an event to the cross sectional area (A_f), arterial compliance (C_f), and pulse transit time (PTT_f) after the event.

$$\sqrt{\frac{A_i}{\rho \cdot C_i}} \cdot PTT_i = \sqrt{\frac{A_f}{\rho \cdot C_f}} \cdot PTT_f \tag{7}$$

This equation can then be solved for the pulse transit time after an event (PTT_f).

$$PTT_f = \sqrt{\frac{C_f / C_i}{A_f / A_i}} \cdot PTT_i \tag{8}$$

From Eq. (8), it can be determined that if the pulse transit time after an event (PTT_f) is greater than the pulse transit time before an event (PTT_i), then the value under the square root bracket must be greater than one. In order for this to happen, the cross-sectional area of the artery must increase proportionally less than the arterial compliance increases. Conversely, if the pulse transit time after an event (PTT_f) is less than the pulse transit time before an event (PTT_i), then the value under the square root bracket must be between zero and one. In order for this to happen, the cross-sectional area of the artery must decrease proportionally less than the arterial compliance decreases.

For this experiment, the mitigating event was the application of local heating and cooling to subjects' arms. If the pulse transit time after the application of local heating (PTT_f) is greater than the pulse transit time before (PTT_i), then the arterial compliance must have increased. However, if PTT_f is less than PTT_i, then the application's effect on arterial compliance cannot be determined. This would require either the cross sectional area to increase due to the event, the arterial compliance to decrease due to the event, or both. Because previous research has shown that the cross sectional area of an artery will increase due to an application of heat with a higher temperature relative to the body[15], the arterial compliance cannot be determined in this case. For the application of local cooling, a positive ΔPTT (defined as $PTT_f - PTT_i$) would mean an effect on arterial compliance cannot be determined, while a negative value would denote a decrease in compliance.

3. Experiment

Data collection took place over the span of one year at Coastal Carolina University. Data was taken from thirty total subjects. These subjects included males and females ages 18 to 50 and were in excellent health. They volunteered to have their data collected for no benefits. The materials used for the collection of data included a laptop with LoggerPro software, a Vernier LabPro sensor, a Vernier ECG sensor, and Kendall Q-Trace resting ECG electrodes. For the local heating, a hot whirlpool (set to 110°F) was used. For the local cooling, a cold whirlpool (set to 53°F) was used.

Experiments were begun by placing electrodes on the right wrist, just below the right elbow, and just below the left elbow of the sitting subject. For each experiment, the positive lead was placed on the electrode on the right wrist, the negative electrode was placed on the electrode just below the right elbow, and the reference lead was placed on the electrode just below the left elbow. This set-up recorded measurements in the radial artery. After all three leads were attached, the subject was asked to relax, and data was collected in LoggerPro for a time interval of ten seconds. The leads and electrodes were then removed from the subject, and the subject was given the application of local heating or cooling. The subjects dipped their right arms up to just above the elbow in the whirlpool. The subjects were asked to keep their arm in the whirlpool for two minutes. The three electrodes were then replaced. With the leads attached, the subject was again asked to relax and data was collected in LoggerPro for ten seconds.

After the completion of data collection, the ECG graphs taken from each subject were then analyzed in LoggerPro. From the graphs, the pulse transit times for each experiment (before and after the local heating or cooling) were determined. This was done by taking the time elapsed from the peak of the R wave to the peak of the T wave on the ECG. The peaks of these waves can be seen in Figure 2. A sample of data collected from the experiment can be seen in Figure 3.

For each subject, five to ten pulse transit times before and after the local heating or cooling were measured. Average PTT's before and after were then determined for each subject. Finally, a ΔPTT was determined for each subject.

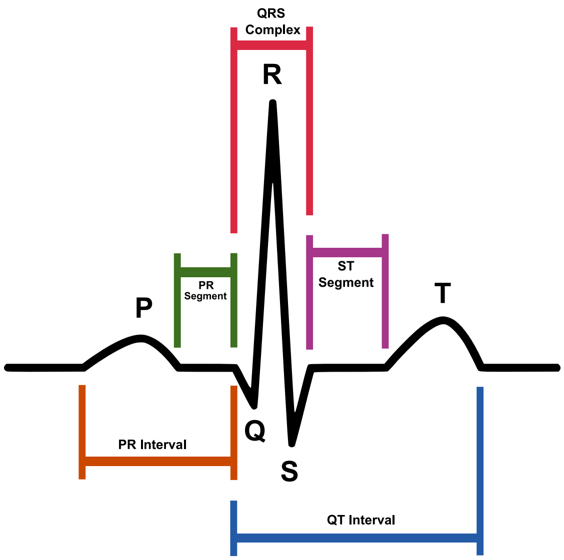

Figure 2. A schematic representation of a normal ECG[18].

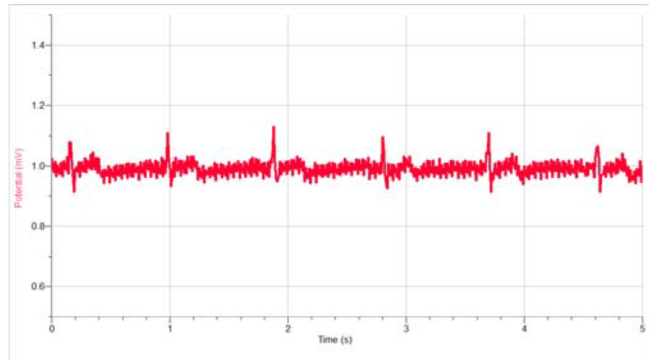

Figure 3. Sample of ECG data collected in LoggerPro.

4. Results

Thirty total subjects were tested. Twenty-three subjects had their data taken with local heating. However, only fifteen of the twenty-three sets of data collected were deemed functional and were used for analysis. The remaining eight samples contained faulty data and were subsequently not used. Some of the data contained very large amplitudes compared to the functional data used. Other faulty data did not resemble an ECG at all and contained no visible waves or peaks. Possible reasons for the faulty data could be attributed to the possibility of an equipment malfunction, recent physical activity of a subject, or possibly human error in the set-up of the equipment. Fifteen subjects had their data taken after local cooling. All fifteen samples taken were deemed functional and were used for analysis.

Of the data that was used for the local heating, the results were consistent with each other. From the ECGs, pulse transit times before the application ranged from 180 ms to 240 ms and averaged 209 ms. Pulse transit times after the application ranged from 210 ms to 300 ms and averaged 231 ms. Fourteen of the fifteen samples of data resulted in a positive value of ΔPTT, and one sample had no change in the pulse transit times before and after the local heating. The values of ΔPTT ranged from 0 ms to 42 ms and averaged a difference of 22 ms (Table 1).

Of the data that was used for local cooling, the results were again consistent with each other. From the ECGs, pulse transit times before the application ranged from 210 ms to 240 ms and averaged 222 ms. Pulse transit times after the application ranged from 190 ms to 250 ms and averaged 210 ms. Thirteen of the fifteen samples of data resulted in a negative value of ΔPTT, and two samples of data resulted in a positive value of ΔPTT. The values of ΔPTT ranged from -30 ms to 44 ms and averaged a difference of negative -11 ms. The data for each subject can be seen in Table 2.

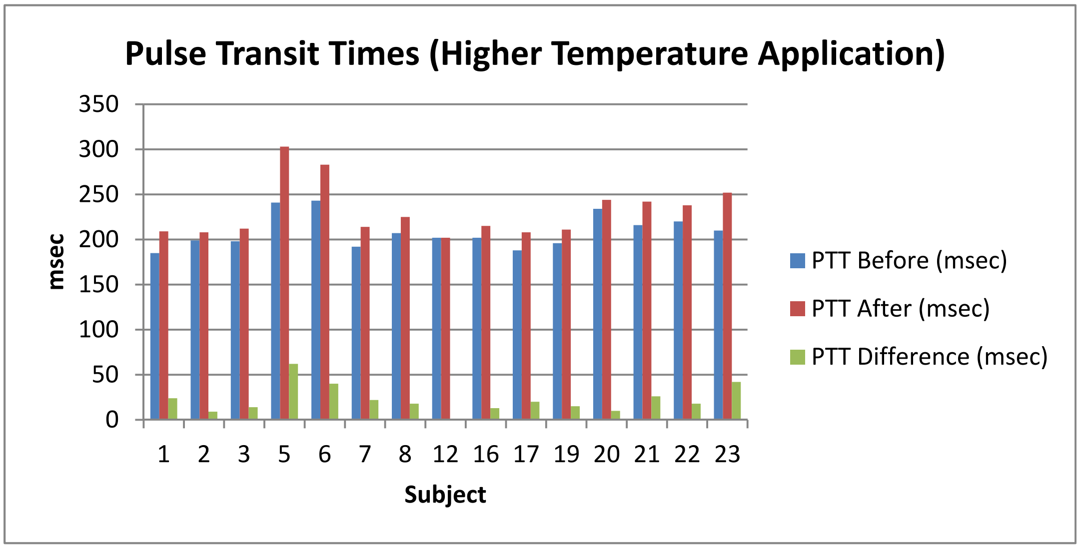

Figure 4. Graph of pulse transit time averages and differences for local heating.

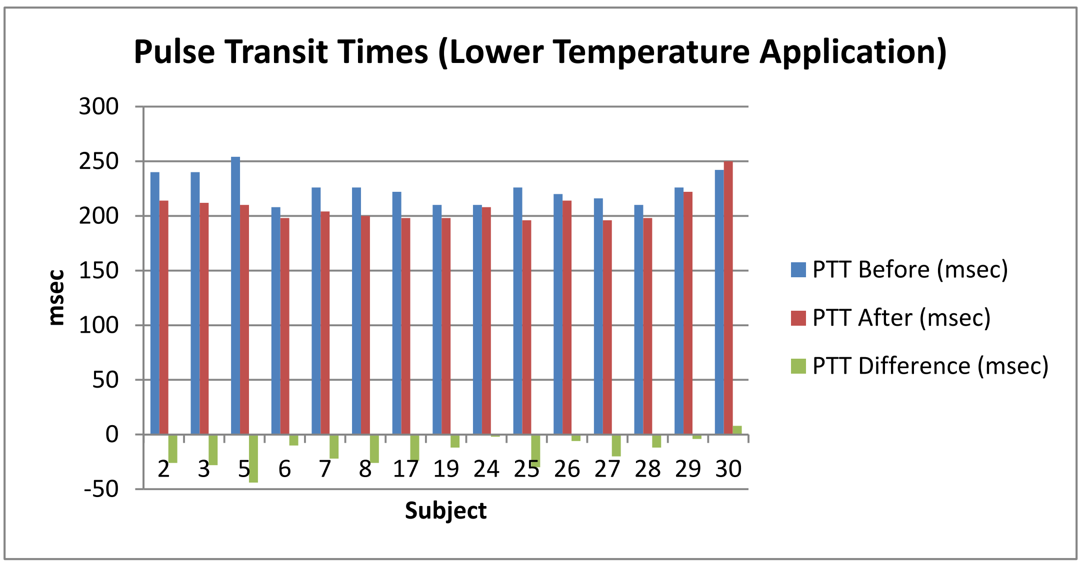

Figure 5. Graph of pulse transit time averages and differences for local cooling.

Subject	PTT Before (msec)	PTT After (msec)	PTT Difference (msec)
1	185	209	24
2	199	208	9
3	198	212	14
5	241	303	62
6	243	283	40
7	192	214	22
8	207	225	18
12	202	202	0
16	202	215	13
17	188	208	20
19	196	211	15
20	234	244	10
21	216	242	26
22	220	238	18
23	210	252	42

Table 1: Data collected for each subject given local heating.

Subjec	PTT Before	PTT After	PTT Difference
2	240	214	-26
3	240	212	-28
5	210	254	-44
6	208	198	-10
7	226	204	-22
8	226	200	-26
17	222	198	-24
19	210	198	-12
24	210	208	-2
25	226	196	-30
26	220	214	-6
27	216	196	-20
28	210	198	-12
29	226	222	-4
30	242	250	8

Table 2: Data collected for each subject given local cooling.

5. Conclusion

The effect of temperature on arterial compliance could be determined from the data collected in the experiment. From the samples used, it was determined that as temperature increases, arterial compliance increases also. The fifteen samples of data after local heating were consistent with each other in showing that as temperature increases, the pulse wave velocity decreases. This, consequently, means the arterial compliance has increased. Fourteen of the fifteen samples of data after local cooling were consistent with each other in showing that as temperature decreases, the pulse wave velocity increases, and arterial compliance has decreased. The one data point with positive ΔPTT can neither confirm nor deny the hypothesis. The results of both local heating and cooling together are consistent with each other in showing that as temperature increases, the compliance of an artery increases also.

6. Acknowledgements

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