A FREQUENCY ANALYSIS OF THE KOROTKOFF SOUNDS

by

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Abstract

The Korotkoff sounds are a result of short, transient vibrations of the arterial wall, induced by the systolic pressure pulse when the intra-arterial and external cuff pressures are similar. The amplitude spectra of these sounds recorded from humans was measured and related to the characteristics of the arterial wall. The frequency of peak amplitude increases as arterial stiffness increases, just as is predicted by the membrane theory. Generation of the high frequency components seems to be related to the longitudinal tension in the artery. Children, whose untethered arteries are under greater longitudinal strain when under the pressure cuff show greater relative amplitudes in the high frequency bands than do adults. This result has also been found experimentally in rubber tubes. Since diastolic pulses show greater relative amplitudes in these high frequencies than do systolic pulses, attenuation of these components is related to the length of the occlusion under the cuff. Furthermore, persons with diagnosed conditions of atherosclerosis show very marked attenuation of the high frequencies of the systolic pulse but not of the diastolic pulse. This indicates that the fatty deposits inside the collapsed portion of the artery attenuate the high frequency sounds.

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I. Introduction

The technique of sphygamomanometry has been used to successfully estimate arterial blood pressure for years. This method relies upon the generation of Korotkoff sounds underneath the pressure cuff. Just as the initiation and cessation of these sounds have proven to be clinically valuable in estimating intra-arterial pressure, the frequency content of these sounds could provide valuable information about arterial properties. Certain characteristics of the Korotkoff sounds have been described qualitatively, such as muffling near diastole and lower pitch sounds in children; however no thorough study has previously been attempted.

The latest and most acceptable theory for Korotkoff sound production is by Anliker and Raman (1). They hypothesize that the arterial wall becomes unstable to circumferencial vibrations when the internal and the external pressures are within a critical range. The sharp pressure pulse provides the perturbation to start this unstable vibration which rapidly grows to an audible sound. Furthermore, the recent work of McCutcheon and Rushmer concludes,

> "These observations suggest that the Korotkoff sounds used as audible criteria for recognizing systolic or diastolic pressures are associated with sudden, transient wall movements produced by the impact of the advancing steep slope of the flow pulse." (2)

Travel et al. (3) find that the Korotkoff sounds are initiated right below the top of the cuff and move down through the occluded portion of the artery with the opening pulse wave.

It is therefore accepted in this paper that the Korotkoff sounds are due to arterial wall vibration, and thus the amplitude spectra* of these vibrations must contain information about the wall characteristics. A diagnostic procedure utilizing this information could become a standard clinical tool, little more difficult to be used than sphygamomanometry.

II. Experimental Apparatus and Procedure

The experimental apparatus is as shown in Figure 1.

Korotkoff sounds were taken on a recording sphygamomanometer developed by Mollo-Christensen and DiMatteo of M.I.T. in 1966 and now being used by Dr. Edward Kass of the Harvard Medical School. The output of this device consists of the Korotkoff pulses plus a square wave pressure index. These signals were separated, rerecorded, filtered into very sharp octave and half octave bands, rectified, and recorded on a four channel Sanborn pen recorder. This allowed for the processing of large numbers of people simply and for the analysis of the frequency content of the individual pulses at the systolic and diastolic ends. The width of the bands does not permit close inspection of the energy content of frequencies closer together than one half octave, but using a wave analyzer which would have fulfilled this requirement better, would not have satisfied the others as well. Also a procedure was maintained which was simple enough so that a similar clinical procedure could be developed easily and inexpensively.

III. Data Analysis

The output from the Sanborn recorder was a series of Korotkoff pulses in five frequency bands and a square wave pressure index. A

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* amplitude spectra = $\sqrt{\text{power spectral density}}$, which shows the frequencies at which the energy of vibration is carried.

typical trance is shown in Figure 2.

In the tracing of each individual's pulses the first systolic pulse was easily found, however an arbitrary definition of the diastolic pulse had to be decided upon. Since the "muffled" sounds which continue down through the diastolic pressure aren't measured in normal sphygamomanometry and since they are of low frequency (below 80 Hz), the last pulse in the center band (160-240 Hz) was taken to be the diastolic pulse. For each person the relative amplitudes of the systolic and diastolic pulses were measured and normalized about the maximum energy band, 80-160 Hz.

The population was divided into groups which would exhibit known trends in arterial characteristics, thereby allowing correlation between these trends and their amplitude spectra. These categories are:

1. Age, it is known clinically that arteries stiffen with age and become more tethered to the surrounding tissues.
2. Average Blood Pressure, average blood pressure is directly related to arterial stiffness and hypertension.
3. Pulse Pressure, the difference between systolic and diastolic pressures, this is the best single measurement of the physical stiffness of the larger arteries if cardiac output and levels of average blood pressure are similar. It is a measure of the stress in the artery necessary for the accommodation of the systolic pulse of blood coming from the heart.

Since athenosclerosis also effects arterial wall characteristics, although through a different mechanism than normal stiffening with age, a special population of people with known conditions of atheroma was studied. This diagnosis was made with standard techniques in the Boston City Hospital clinic. In fact, most individuals were post heart attack patients.

IV. Results and Discussion

Refer to Figures (3 through 8) for the systolic and diastolic amplitude spectra of the above groups in connection with this discussion.

The frequency of peak amplitude of the Korotkoff sounds is between 80 and 160 Hz in all cases. This relatively wide, one octave band does not show clearly how the peak frequency changes with the parameters discussed, but the next band, 160 to 240 Hz does show the expected trend. The relative amplitude in this band increases with all the previously mentioned arterial stiffness indicators. Since the amplitude spectra curves of Korotkoff sounds are quite smooth, this trend exhibits the fact that the amplitude peak moves to a higher frequency as stiffness increases. This result is quite compatible with all simple membrane models of vibrating tubes which show

$$\sigma^2 \sim Eh$$

where σ is the frequency of vibration, E is Young's modulus of elasticity, and h is the arterial thickness. One might like to be able to derive stiffness, Eh, from a measurement of the peak frequency, however, any error in this measurement would cause a larger error in the calculated stiffness. Arterial stiffness in the absence of atheroma is probably better estimated by considering age and pulse pressure.

In measuring amplitude spectra, the amplitude must be normalized about a specific point; in this case taken to be the amplitude of the band containing the fundamental frequency, that frequency at which most of the energy is concentrated. Only relative to the fundamental can the generation and attenuation of frequency components can be compared among groups of people. Since the high frequency vibrations (240-540 Hz) contain much less energy than the fundamental frequency, their relative amplitude is more sensitive to changes in the properties of the arterial wall. For these reasons the band containing the fundamental peak was made one octave wide, to ensure that it contained the fundamental peak and that normalization of the more interesting, half octave, high frequency bands would be reliable.

Because the Korotkoff sounds are recorded distal to the pressure cuff, both generation and attenuation phenomena through the length of the cuff must be considered in order to understand the significance of the measured amplitude spectra. Generation of the high frequency components has been shown to be related directly to the longitudinal tension in the artery under the cuff. Attenuation is related to the length of the occlusion under the cuff. A look at recent experimental work concerning these mechanisms will help in this discussion.

McCutcheon and Rushmer have made plastic casts of canine brachial arteries subjected to a pressure cufff. Intra-arterial and external cuff pressures were varied. They found that when the cuff pressure greatly exceeds the intra-arterial pressure, the artery flattens just as has been hypothesized by the rubber tube experiments. Its circumference changes little from its normal circumference. However, as intra-arterial pressure increases to near the cuff pressure, the artery becomes elliptical in cross section and its circumference decreases to half of its normal size. The arterial wall is incompressible and has a Poisson's ration close to .5, and since it is only free to move longitudinally, the large internal and external pressures drastically stretch the artery in that direction. McCutcheon and Rushmer tested only young canine arteries in obtaining these results. However it is well known that arteries become tethered to their surrounding tissues with age. The longitudinal stretching required for the maintenance of this reduced circumference situation is hindered, for the longitudinal stress is spread over all of the less elastic tissues instead of just the arterial wall. Thus, the situation they described is good only for children and cannot be applied to older people with tethered arteries. The collapsed rubber tube models are not as bad as they predict.

Schoenberg measured the amplitude spectra of Korotkoff sounds generated by latex tubes. His experimental apparatus is shown in the appendix. Upon increasing longitudinal tension in the tube, he found a secondary peak in the amplitude spectra, about 1 1/2 to 2 octaves above the fundamental peak. See Figure (A1).

Figures (3 and 4) exhibit how the relative amplitudes of the frequency components decrease with age. The explanation developed above relates this phenomenonto increased tethering which decreases the longitudinal tension and therefore the generation of these high frequency vibrations. The secondary peak found by Schoenberg is very apparent in the spectra of the children.

Figure 9 shows that the relative amplitude of the high frequency components at diastolic cuff pressure are greater than those at systolic cuff pressure. This is the opposite of the expected result, so obviously another parameter must be involved. This parameter is probably the length of the occluded section of the artery under the cuff. McCutcheon and Rushmer showed that at systolic cuff pressures the artery is occluded from just below the top of the cuff to the bottom. As cuff pressure is decreased to diastolic, the length of the occluded section also decreases. In fact, the diastolic pressure is measured by the last pulse which occurs just before occlusion ends completely. A logical explanation for the different intensities of the high frequency parts of the Korotkoff sounds at diastole and systole is that their attenuation is related directly to occluded length of the artery under the cuff.

The most significant result of this analysis is its application to the diagnosis of atherosclerosis. See Figure 3. People suffering from athersclerosis show very significant attenuation of the high frequency, systolic Korotkoff vibrations. This might be due to the build up of fatty deposits in the brachial artery which damp these sounds when the artery is occluded. This effect is much more pronounced at systole than it is at diastole. See Figure 4. Since the fatty deposits of atheroma are not uniformly distributed, the longer the length of the occluded artery, the greater is the probability of a major plaque being present and attenuating the vibrations. In fact at systole, the length of the occlusion is an order of magnitude greater in scale than that of the atheromic plaques. Furthermore, in the tethered arteries of the people in the age group subject to atheroma, the artery is flattened in cross section at systolic cuff pressures. It is quite reasonable that fatty deposits between the two vibrating sides of the flattened artery could be capable of causing a relative attenuation of the higher frequency modes. Thus, there is a high probability that this attenuation effect will be seen if a significant degree of atherosclerosis is present. Of course whether the degree of high frequency attenuation can be proven to be a good measure of the severity of atherosclerosis must still be studied.

V. Statistical Reliability

Since the population was divided according to age, average blood pressure, and pulse pressure; individual variation of the amplitude spectra is great. From the previous discussion it is clear that these groups should not be homogeneous, for there are many factors which effect the amplitude spectra, none of which is completely confined to any of these groups. In contrast to those groups, the people known to be suffering from atherosclerosis do constitute a nearly homogeneous group. The standard deviation in the two highest frequency bands is about .1, which means that over 80% of the people in this group lie below the mean of any other goup. It must be remembered also that these other groups are not devoid of people suffering from athersclerosis, thereby substantially lowering their group average. Thus, the attenuation of high frequencies in the systolic Korotkoff pulse of people suffering from more advanced cases of atherosclerosis is statistically reliable.

VI. Conclusions

1. The frequency of maximum energy of the Korotkoff sounds is directly related to the stiffness of the arterial wall.

2. The amplitude of the high frequency components is a function of the longitudinal tension in the artery under the cuff and of the length of the occluded section of the artery. Tethering of the artery to the surrounding tissues is very important in limiting the longitudinal tension applied to the artery by the pressure cuff.

3. People with diagnosed conditions of atherosclerosis show significant attenuation of frequencies above 240 Hz in their systolic Korotkoff sound pulses.

This was a pilot study designed to find information in the Korotkoff sound amplitude spectra which could be of clinical value. Much of the information gained agrees quite well with recent theoretical and experimental work concerning these sounds. However, the main contribution of this study is that it provides the prospect of a fast, easy, inexpensive, external means of diagnosing atherosclerosis. This could be of immense clinical value. Further studies must be undertaken to eliminate variables not herein considered. Larger populations must be used, and arteries must be dissected to determine if the degree of atherosclerosis can be measured by the degree of the high frequency attenuation of the systolic Korotkoff sounds.

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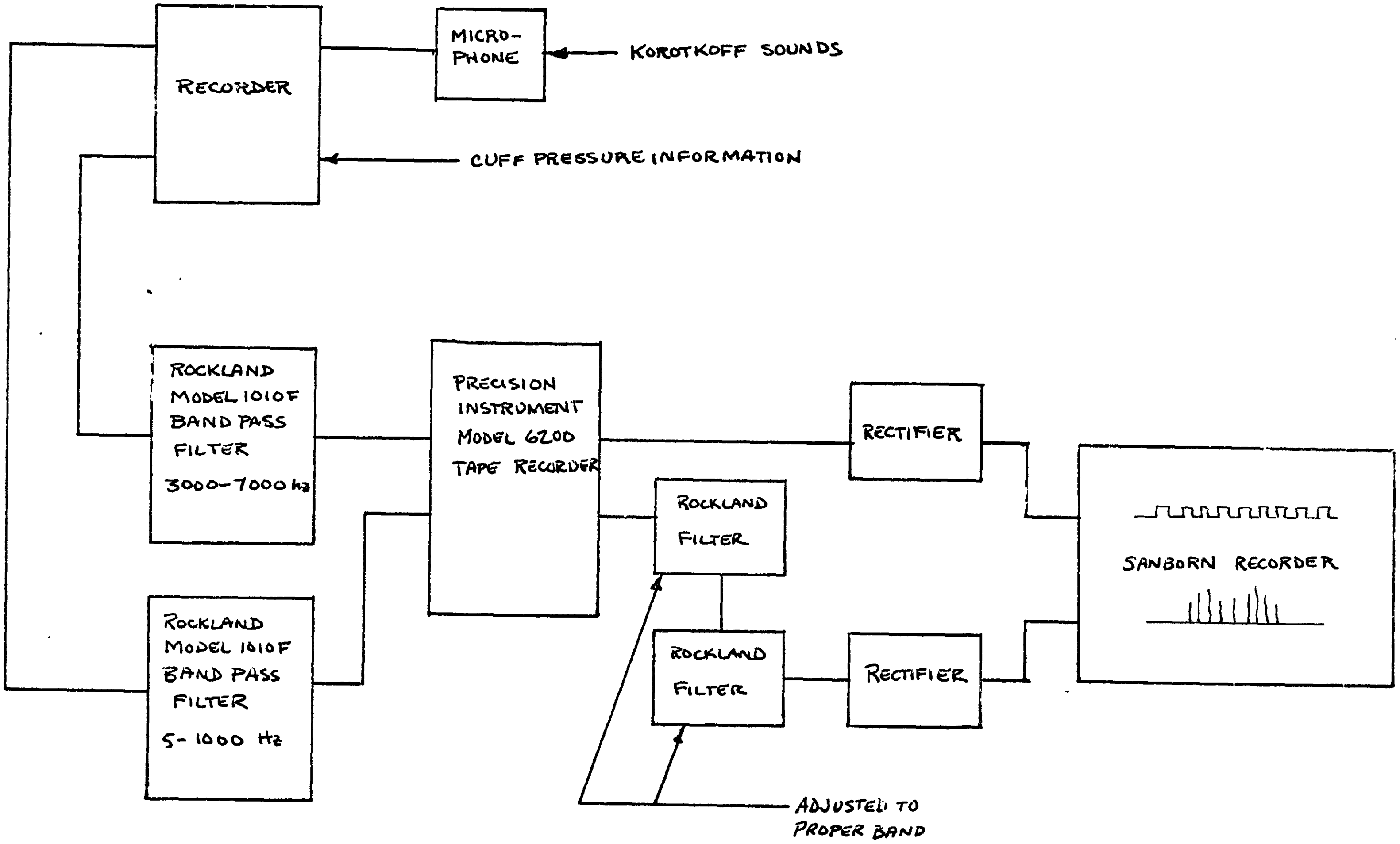

Figure 1. Experimental Apparatus

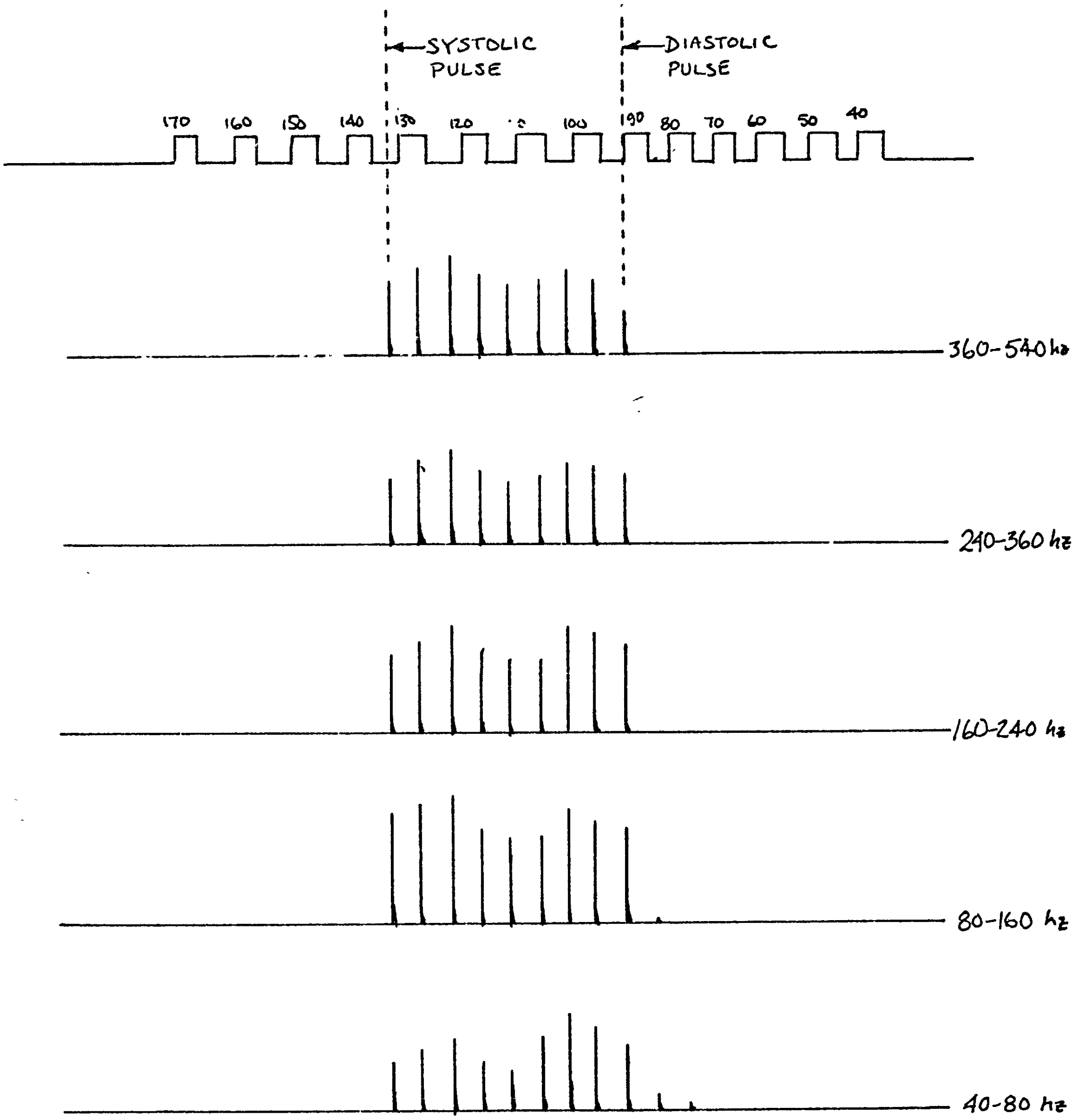

Figure 2. Typical Traces

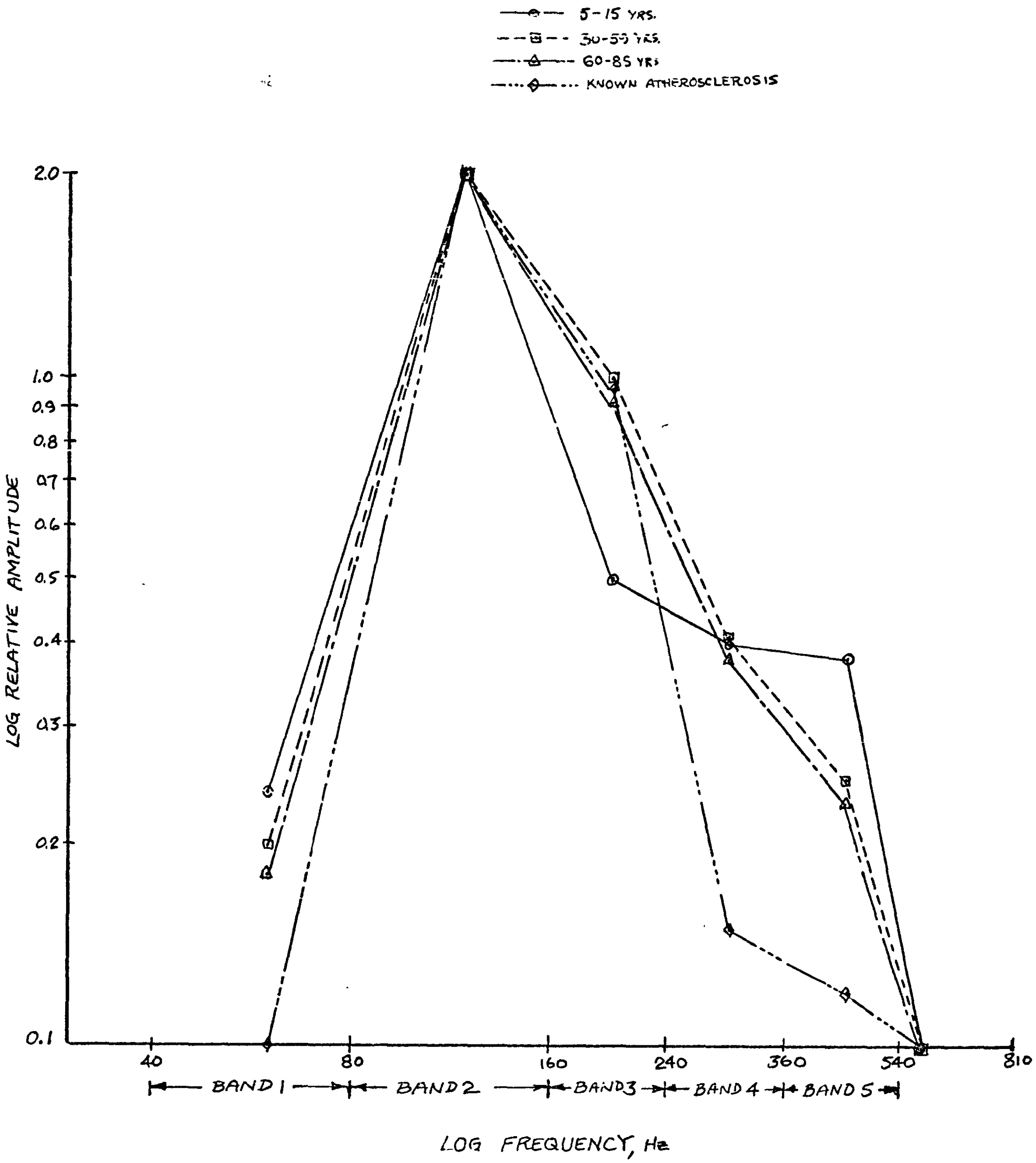

Figure 3. Amplitude Spectra of Systolic Pulse, vs. Age

Note - Points are plotted at the center frequency of each band. Connecting lines are drawn for visualization purposes. No output was seen in the 20-40 and 540-810 frequency bands.

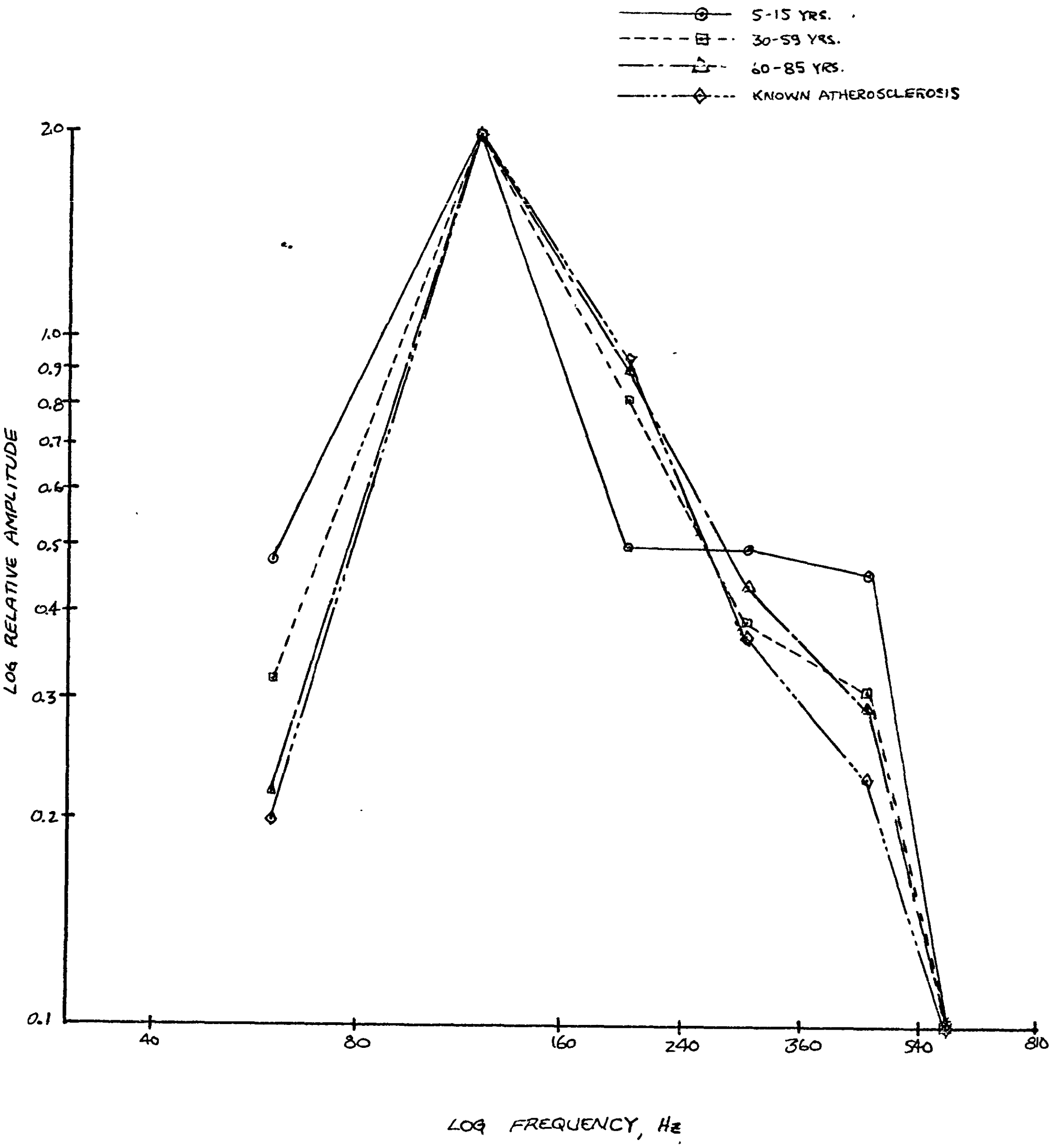

Figure 4. Amplitude Spectra of Diastolic Pulse vs. Age

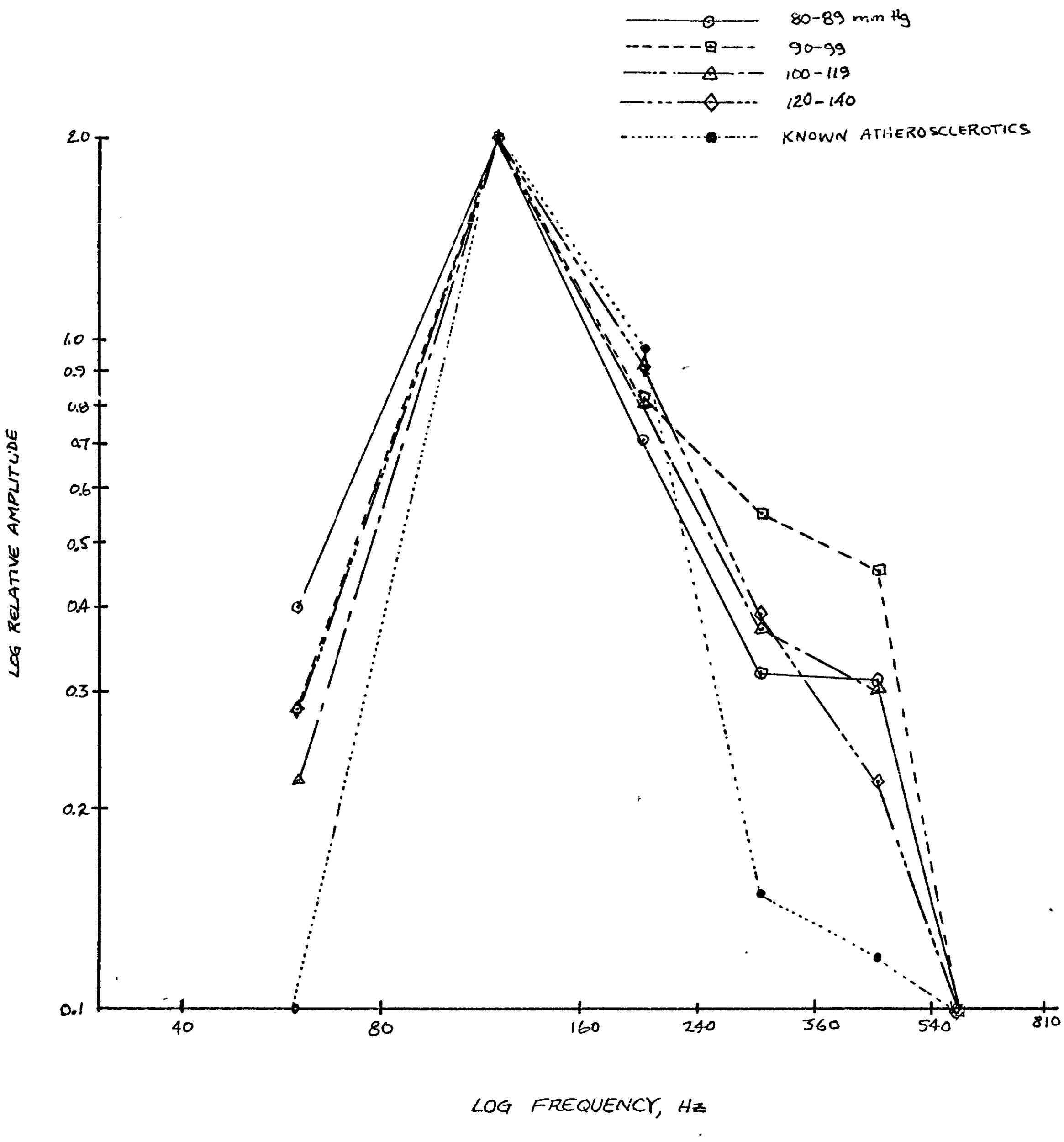

Figure 5. Amplitude Spectra of Systolic Pulse vs. Average Blood Pressure

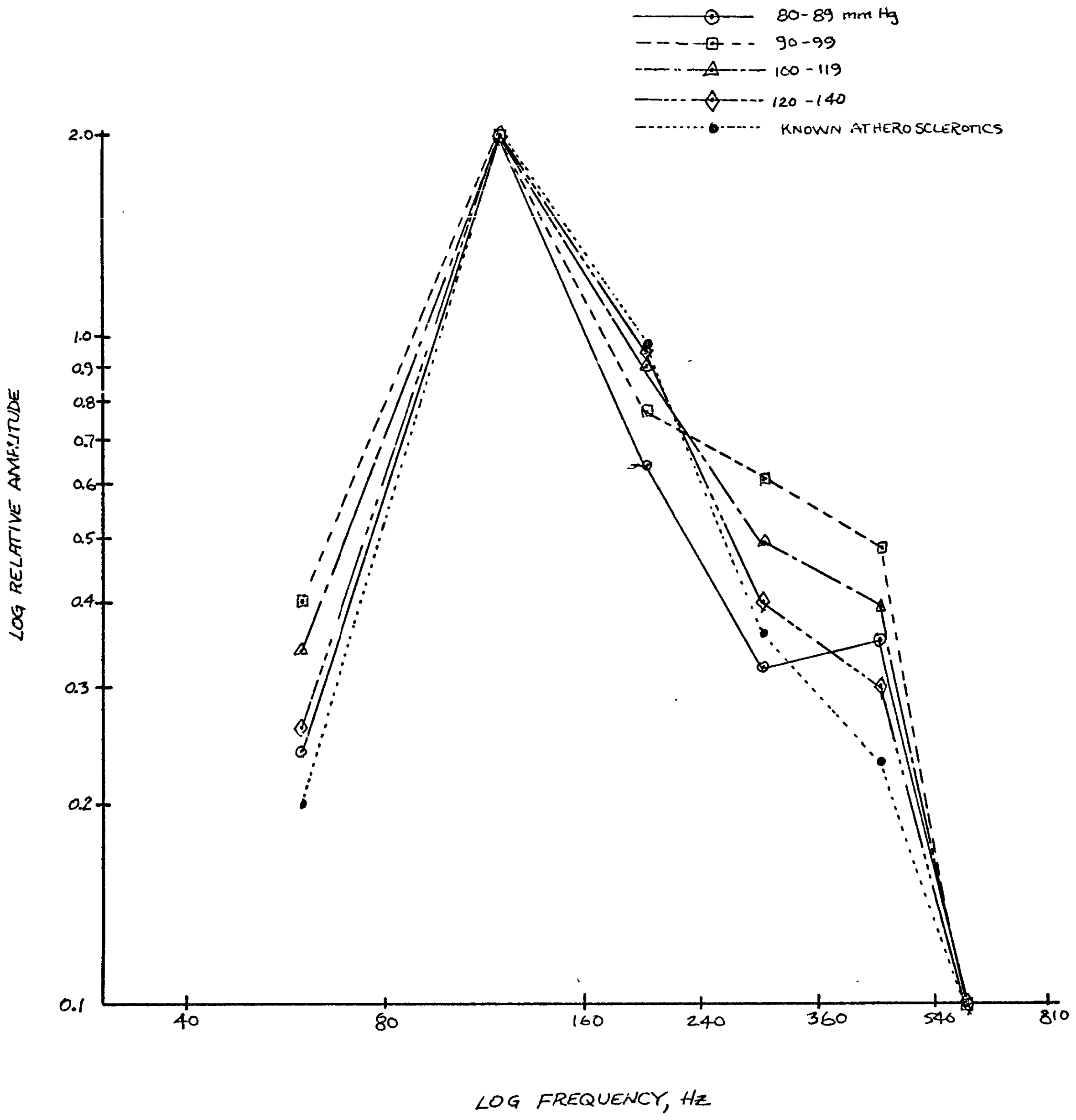

Figure 6. Amplitude Spectra of Diastolic Pulse vs. Average Blook Pressure

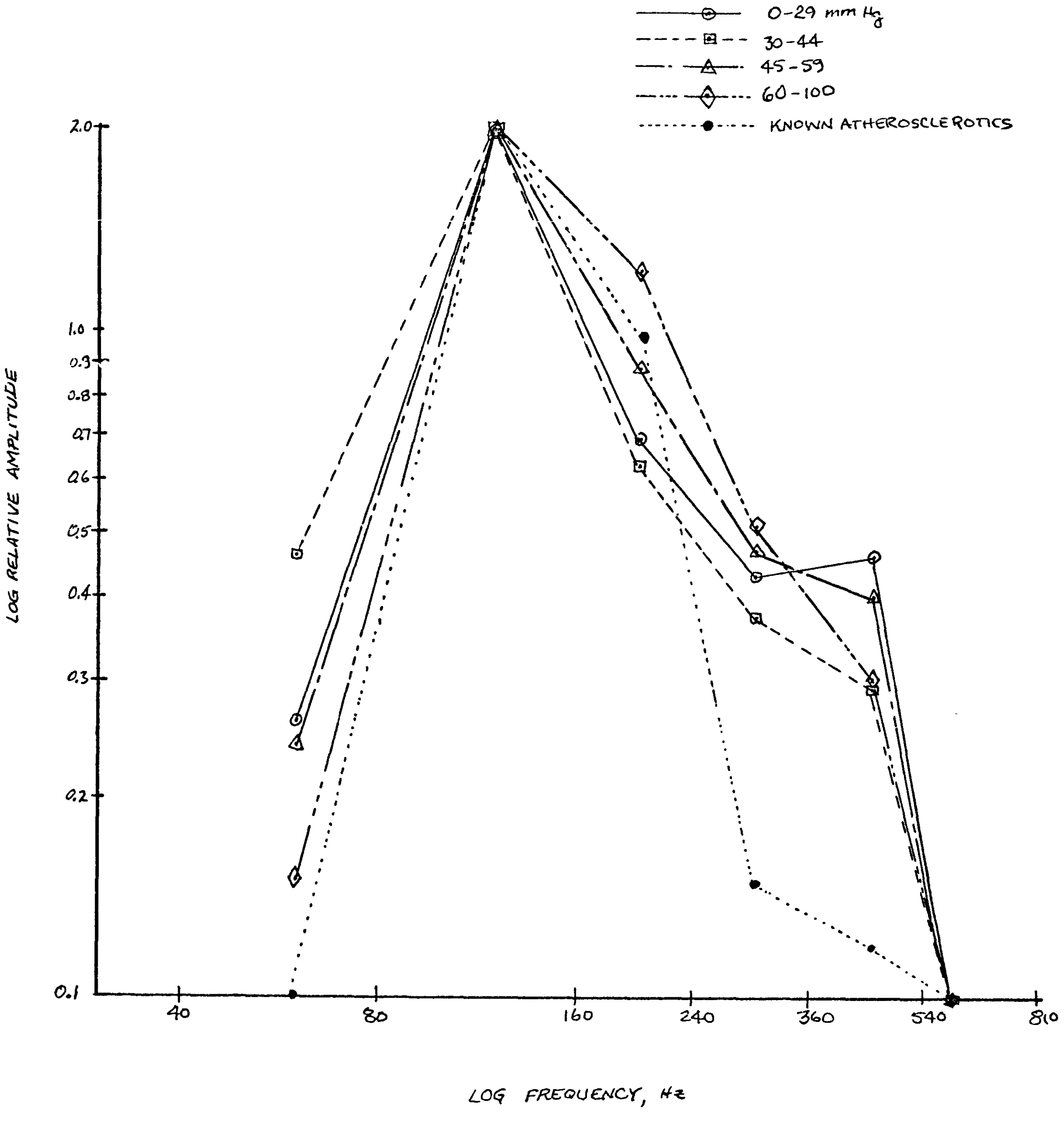

Figure 7. Amplitude Spectra of Systolic Pulse vs. Pulse Pressure

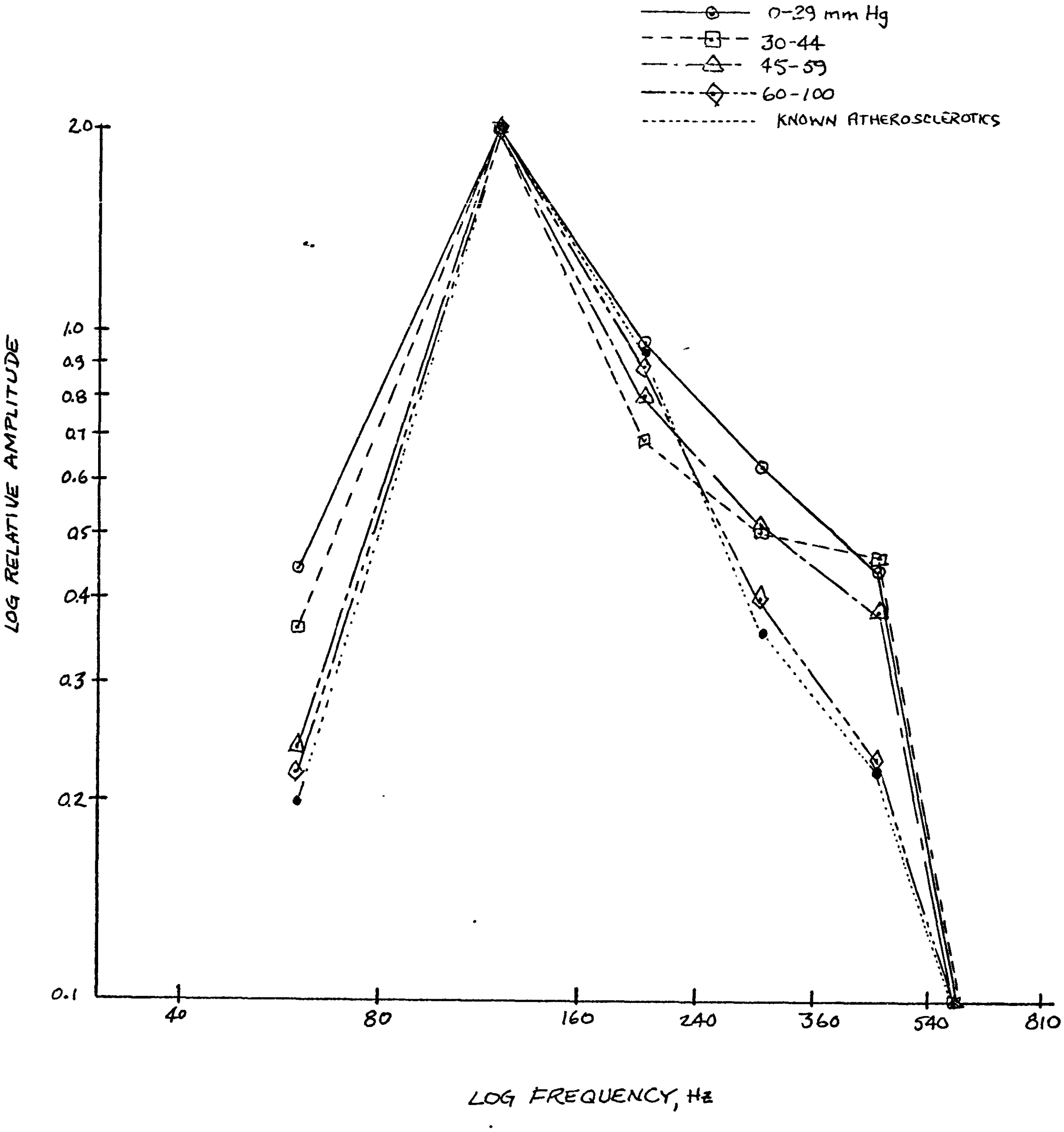

Figure 8. Amplitude Spectra of Diastolic Pulse vs. Pulse Pressure

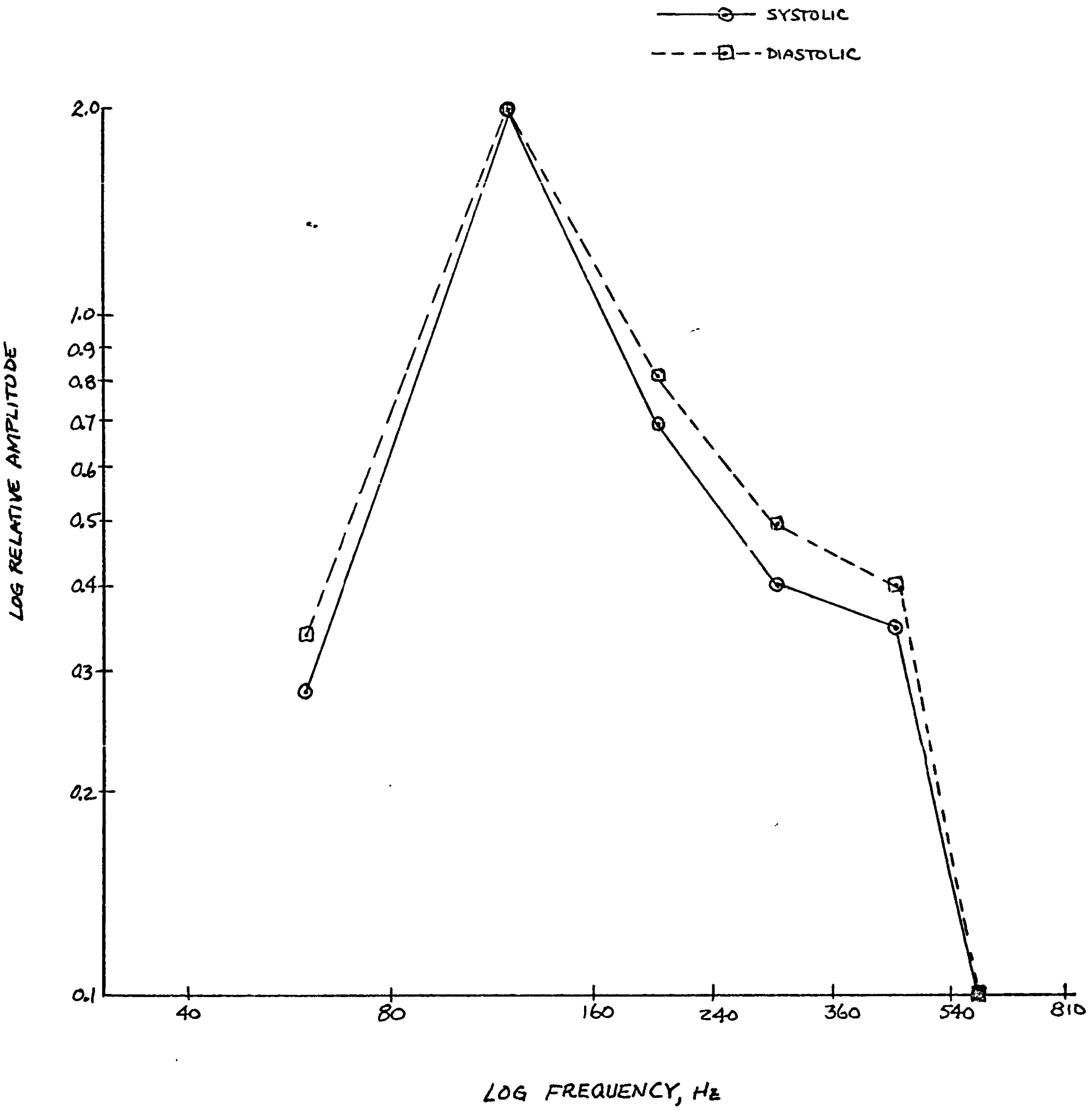

Figure 9. Amplitude Spectra of Systolic and Diastolic Pulses

Appendix

Mark Schoenberg, in this laboratory, measured the amplitude spectra of the Korotkoff sounds generated by latex tubes containing a pulsing water flow, His apparatus is shown in Figure A1. This system retained similarity to the natural system through the accurate matching of certain nondimensional characteristics to those of the in vivo artery. These are:

1. The ratio of the mean pressure to the Young's Modulus of elasticity, $\overline{P}/E$
2. The pulse pressure to Young's Modulus ratio, $\Delta P/E$
3. The thickness to radius ratio, h/R_o

The following table shows a comparison of the experimental system and the human brachial artery in terms of these dimensionless parameters.

Parameter	$\overline{P}/E$	$\Delta P/E$	h/R_o
Experimental System	.017	.007	.25-.125
Human Brachial Artery	.02	.008	.2 -.1

The main result of Schoenberg's experiment which is pertinent to this paper is his discovery of air increase in high frequency amplitude with an increase in longitudinal tension. Figure A2 shows the effect of the amplitude spectrum of impressing a longitudinal strain equal to 20% of normal length on the simulated artery.

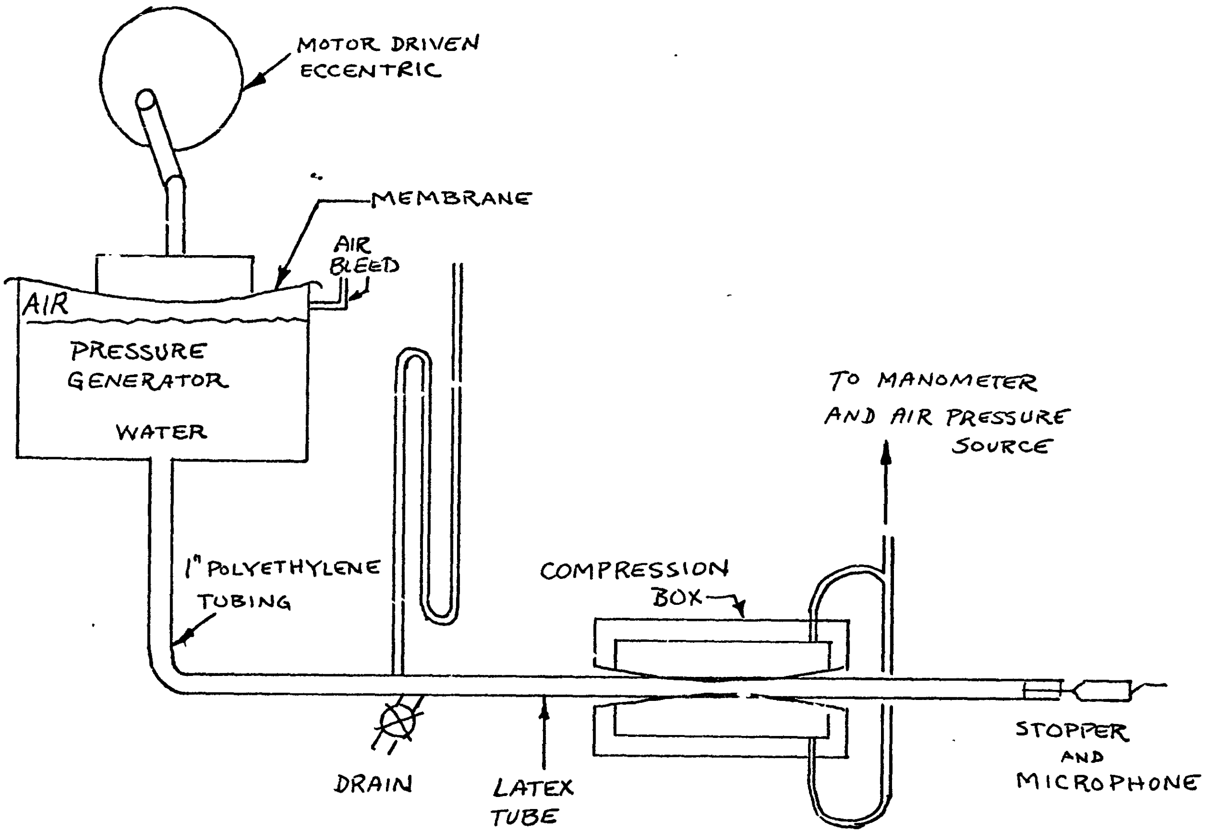

Figure A1. Experimental Apparatus

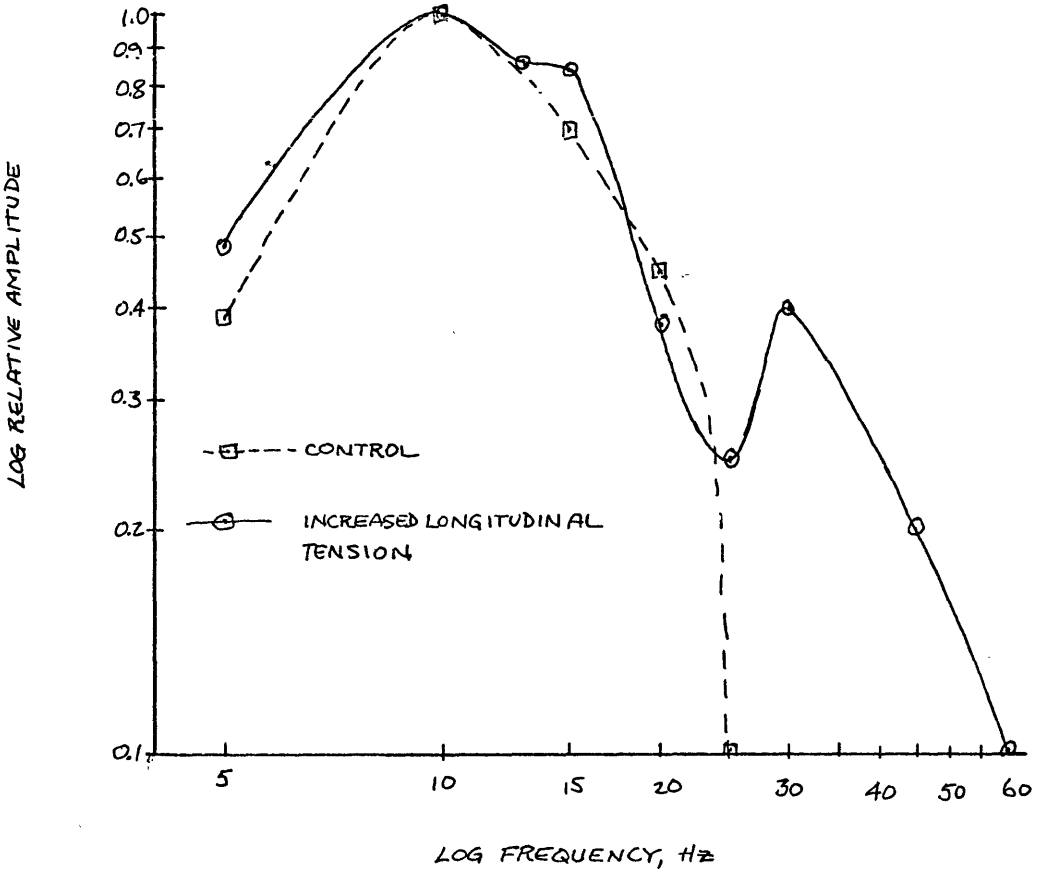

Figure A2. Amplitude Spectra vs. Longitudinal Tension