Korotkoff Sounds
AN EXPERIMENTAL CRITIQUE

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ABSTRACT

The Korotkoff sounds which serve as criteria for sphygmomanometry are composed of at least two components, (1) an initial transient (K\textsubscript{i}), and (2) a more prolonged "compression murmur" (K\textsubscript{c}). In this experimental survey, the Doppler flow detection device was used to acquire evidence indicating that K\textsubscript{i} occurs at the very onset of flow under the cuff and probably represents an acceleration transient producing abrupt displacement of the arterial wall and surrounding tissues distal to the point of compression. It is nonspecific in nature and can be simulated by tapping the skin of the hand. K\textsubscript{c} follows the initial transient and appears to represent audible sounds from turbulence or eddies in the blood flowing from the constricted artery under the cuff. Muffling seems attributable to the attenuation of frequencies between 60 and 180 cycle/sec, as the initial transient sound disappears, leaving the "compression murmur" as the muffled sound. Studies of cineangiograms and casts of arteries demonstrated that the arterial lumen under the cuff is primarily tapered and that the circumference of the artery shrinks considerably as the wall is unloaded by decreased transmural pressure. In contrast, rubber tubes become unstable and flatten into a binodal configuration when externally compressed. It seems doubtful that rubber tubes constitute adequate models for arteries in situ in the study of the genesis of Korotkoff sounds.

ADDITIONAL KEY WORDS sphygmomanometry arterial compression arterial models arterial cineangiograms arterial casts compression murmurs sound analysis Doppler flow detection anesthetized dogs unanesthetized man
rotkoff (1) before the Imperial Military Medical Academy in St. Petersburg (1905).

"The cuff of Riva-Rocci is placed on the middle third of the upper arm, the pressure within the cuff is quickly raised up to the complete cessation of circulation below the cuff. Then, letting the mercury or the manometer fall, one listens to the artery just below the cuff with a children's stethoscope. At first, no sounds are heard. With the falling of the mercury in the manometer down to a certain height, the first short tones appear; their appearance indicates the passage of part of the pulse wave under the cuff. It follows that the manometric figure at which the first tone appears corresponds to the maximal pressure. With the further fall of the mercury in the manometer the systolic compression murmurs are heard, which pass again into tones (second). Finally all sounds disappear. The time of the cessation of sounds indicates the free passage of the pulse wave; in other words, at the moment of the disappearance of the sounds, the minimal blood pressure within the artery preponderates over the pressure in the cuff. Consequently the manometric figures at this time correspond to the minimal blood pressure."

Three distinct types of sounds were included in the original description; the tone, the compressional murmur, and tones (second) which apparently corresponded to sound muffling. In 1914, MacWilliam and Melvin (2) concluded that "muffling" of the sounds corresponded to diastolic pressure. Their direct observations indicated that the sounds were the result of a localized sudden change in shape of the compressed arterial segment and that this change in shape coincided with the arrival of a pressure wave.

For many years thereafter consideration of wall movements was neglected, flow-dependent factors being presented as primary sources of Korotkoff sounds. Erlanger (3), in 1916, first proposed a water-hammer mechanism and later realized that the sound originated in the compressed portion of the artery, at a point where water-hammer could not possibly develop (4-5). He then described an increase in steepness of the pulse front as it progressed through the flattened artery and theorized that this led to disturbances which produced the sound (4-5). Bramwell (6) postulated breaking of the steep wave front as a cause of the disturbances. Conclusions similar to those of Erlanger and Bramwell were reached by Lange et al. (7-8). Their theory required a linear increase in mean flow velocity during diastole. They postulated two phases of relatively steady, quiet flow separated by a brief period of unsteady or turbulent flow which induced movement of the vessel wall and produced both spontaneous or "pistol-shot" sounds and the Korotkoff sounds.

Korotkoff sounds have been attributed to various types of fluid-induced vibrations such as turbulent jets (9), turbulent wakes (10-11), cavitation (12), systolic impact, stenotic flow and protodiastolic recoil (13), resonating of the arm as the pulse enters (14), and Bernoulli effects or "flutter" (15). Most recently Anliker and Raman (16) and Raman (17) studied rubber tubes and developed a mathematical derivation which exhibited transient instability in response to small perturbations. They postulate a type of hydraulic amplification of local flow disturbances, to the point that they become audible. Thus, Korotkoff sounds were attributed initially to wall movements, later to unstable flow and finally to a diverse combination of factors. No hypothesis of sound production is generally accepted as the cause of Korotkoff sounds.

A more comprehensive picture of the genesis of Korotkoff sounds requires definitive information regarding a number of variables. The most important of these are the changes in geometry of the artery during compression and occlusion by external pressure, the relationship of the configuration of the arterial channel under the cuff to the cardiac cycle and to different cuff pressures, the distribution of increased pressure in the tissues under the occluding cuff, the mechanisms producing audible sounds, and the relation of the sounds to changes in blood pressure and blood-flow velocity in the segment of the ar-
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tery under and distal to the cuff. This paper reports the results of a series of studies of some aspects of these basic questions using a model, dogs, and human subjects.

Collapse of Rubber Tubes and Arteries

There is general agreement that Korotkoff sounds are related to the compression of the artery underlying the cuff. The changes in the configuration of the arterial channel associated with different degrees of external compression is clearly a point of departure for studying the mechanism of sound production. Since arteries are rather inaccessible, it is most convenient to study collapse phenomena using a rubber tube with elastic properties resembling an artery as closely as possible (18, 19). Such a study was conducted using latex tubing of various wall thicknesses, 1/2 to 1 inch in diameter, and 24 or more diameters in length. Rigid mounts secured the test lengths inside a Lucite box (Fig. 1A). The pressure in the box was increased in 10 to 20 steps until the tube collapsed maximally. Externally-controlled micrometers were positioned to measure the tubing diameter change in the minor axis of the elliptical section. The system accuracy was ±0.0005 inches. At zero transmural pressure, the tube was almost exactly circular. With increasing pressure the mid-section of the tube became elliptical and finally collapsed into a binodal form as expected from theory (Fig. 1B). In each test a region of "pseudoinstability" was observed over which a small change in external pressure produced large deformations. For example, in a tube with wall thickness-to-lumen ratio of 0.161, the ratio of minor axis (Dmin) to initial average diameter (Davg) decreased very slightly (less than 5%) as the pressure was increased.

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A. PRESSURE SOURCE
MICROMETER CONTROL
LATEX RUBBER TUBE

B. Dmin / Davg

FIGURE 1
Characteristics of compressed rubber tubes. A. The apparatus used to measure the dimension change of the tube as it is collapsed by increasing transmural pressure. The tip of the pointer is at right angles to the control assembly. Contact of tube and pointer was precisely controlled by noting completion of the circuit between the pointer and conductive paint on the tube surface. The tube position was constant throughout a run. B. Results for a tube with wall thickness-to-lumen ratio of 0.161. The dashed line (T) is the predicted behavior calculated from small deformation theory. The solid line (E) is the experimental behavior. Small deformation theory evidently does not fit this situation.

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from zero to 2.5 psi (129 mm Hg). Above that level of transmural pressure, $D_{min}$ diminished very sharply (Fig. 1B).

Systolic and diastolic pressures obtained by direct arterial puncture have correlated well with corresponding values based on sphygmomanometry (20-23). If the brachial artery behaved like a rubber tube and required a positive external pressure to produce collapse, all sphygmomanometer values for systolic and diastolic pressure measurements should be too high. An extensive analysis by Anliker and Raman (16) of sound production in rubber tube models led them to conclude that "The auscultatory systolic pressure is higher than the maximum of the intra-arterial pressure with the stiffness effects of the strongly curved surfaces included" (16). Extremely high external pressures are required to completely occlude the lumen of a thick-walled gum rubber tube. In contrast, the lumen of an artery is easily occluded by a simple ligature, as any surgeon will testify. These observations suggest that analysis of collapse of thick-walled rubber tubes external pressure is probably not applicable to compression of arteries.

**CINEANGIOGRAMS OF COMPRESSED CANINE BRACHIAL ARTERIES**

Cineangiography was used for dynamic visualization of arterial channels in the fore-

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**FIGURE 2**

A. The results of cineangiograms of compressed canine brachial arteries shown schematically. The solid lines indicate the shape of the arterial wall at diastolic pressure levels. The dotted lines indicate the change in the arterial wall produced by arrival of the pressure wave.  
B. Photographs of four representative casts are positioned adjacent to the illustration of the relationship between the artery and the cuff when the casts were obtained. Note that lateral and superior views reveal diminished diameter indicating reduced circumference resulting from unloading of the wall.
limbs of dogs during deflation of pressurized cuffs. The dogs were anesthetized with sodium pentobarbital (20 mg/kg). The subclavian artery was catheterized from the femoral artery and a cannula was inserted into a peripheral artery in the forepaw with the catheter tip pointing toward the heart. A cuff around the upper forelimb was inflated until forepaw arterial pressure demonstrated complete occlusion of the vessel. Radiopaque material (90% Hypaque) was hand-injected into the subclavian artery as the cuff was deflated. The changes in the artery under the cuff were recorded by 16-mm cineangiograms filmed at 16 frames/sec. Filming was stopped after the forepaw pressure had returned to control levels for several beats.

Ten angiograms were obtained from 4 animals (Fig. 2A). With cuff pressures above systolic levels, the opaque fluid column was observed to pulsate against a point of occlusion at the upper margin of the cuff. As the cuff pressure was decreased 2 to 3 mm Hg/beat, the fluid column began to penetrate the vessel under the cuff with each systolic pulse. As cuff pressure reached arterial systolic pressure, the pulsating fluid column under the cuff approached the center of the cuff with each beat.

Just below systolic pressure, a brief, tiny jet could be seen distal to the constricted region under the center of the cuff. A pressure rise of approximately 5 mm Hg was detected downstream coincident with appearance of the jet. This jet filled only a short portion of the distal artery and then the distal opacification disappeared. The downstream artery appeared to have an expanding taper during the brief time it was filled. As cuff pressure continued to decrease, two or three more discrete jets could be identified before persistent downstream opacification prevented identification of succeeding pulsations. The artery appeared partially compressed until cuff pressure was below the arterial diastolic level. A similar sequence was observed when the artery was opacified before cuff inflation.

Based on the responses of a thick-walled rubber tube, we expected the artery to be flattened to a wedge shape and were rather surprised to discover so little evidence of this configuration on the films (see Fig. 2, top). The leading edge of the opacified blood appeared to be tapered to a fine point under the cuff so long as the inflation pressure exceeded arterial systolic pressure. This observation suggested the possibility that the tapered portion of the artery was either circular or elliptical. It therefore seemed desirable to use another technique for checking the configuration of constricted arterial segments under a cuff.

**THREE-DIMENSIONAL CASTS OF COMPRESSED CANINE LIMB ARTERIES**

Plastic casts of arteries were prepared to preserve configuration of segments that were compressed under an inflated cuff. Immediately after sacrifice of the dog, the limb artery was cannulated at least 5 cm proximal to its entrance into the limb. An adult blood pressure cuff was positioned around the upper portion of the limb. A low viscosity mixture of polyester resin, catalyst and accelerator was proportioned so that the mixture would solidify within 10 min. This material was infused under constant pressure through the proximal catheter either before or after cuff inflation. The cuff pressure was set at either zero or 100 mm Hg and the infusion pressure was held at levels 20 to 200 mm Hg higher than the cuff pressure. All relationships were carefully maintained until the resin had set. The artery and its contained cast were then dissected from the limb for study.

Sixteen casts were obtained from the limbs of 10 dogs weighing 16 to 28 kg. Four representative casts were mounted and photographed (Fig. 2B). At zero cuff pressure the arterial lumen was cylindrical, like a vessel filled with blood or contrast material during life. The casts made at maximum cuff pressure and minimum infusion pressure tapered quickly into a flattened empty vessel under the cuff. The flattening began at the proximal margin of the cuff. At increasing infusion pressures, the cast material entered the vessel under the cuff, and the artery was roughly
elliptical, although it was not always symmetrically compressed.

In contrast to a rubber tube, the arterial circumference was considerably diminished as the lumen tapered and flattened. For example, the circumference of the artery above the pressurized cuff was compared with the circumference at the point of greatest constriction for the artery under the cuff (Table 1).

The circumference decreased only 10 to 15% in the casts of four vessels with zero cuff pressure. The much larger decrease in circumference of the compressed vessels signifies that reduced transmural pressure across the artery allows the vessel to contract as its wall is unloaded. Indeed the surfaces of the displayed casts (Fig. 2B) had fine, evenly spaced, longitudinal wrinkles in the constricted regions analogous to the changes described by Van Citters et al. (24) for constricted small arteries. Latex tubes do not show similar changes. To avoid unrealistic compromises required with rubber models and dog arteries, a series of subsequent observations were made on human subjects.

**Characteristics of Korotkoff Sounds from Human Arteries**

Korotkoff sounds can be recorded from a microphone positioned over the brachial artery distal to a sphygmomanometer cuff inflated to pressures between systolic and diastolic levels. These oscillograph waveforms typically

![Characteristics of Korotkoff sounds. A. The Korotkoff sound compared to the simulated sound produced by briskly tapping the back of the hand. Indicating the nonspecific character of the vibrations, differences between the two waveforms are difficult to detect. B. The frequency components of Korotkoff sounds recorded just before muffling (upper line), the muffled sound (middle), and the sounds recorded below muffling (bottom line). Note the attenuation of the frequencies above 60 cycle/sec, and the correspondence of this attenuation to the occurrence of muffling.](http://circres.ahajournals.org/)

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consist of a few high amplitude deflections (Figs. 3A, 5 and 6). As cuff pressure descends, the initial brief train of pressure waves is followed by low amplitude deflections persisting for longer intervals. The low amplitude, high frequency deflections then decrease as cuff pressure reaches diastolic levels. Alterations in these perturbations represent the characteristic audible changes used for the subjective indication of diastolic pressure. The initial vibrations can be displayed on a sound spectrogram with the sound frequency represented on the vertical axis, the intensity at each frequency indicated by the blackness of the record, and time indicated along the horizontal axis (Fig. 3A). This illustration confirms the subjective impression that there are no dominant fundamental or harmonic frequencies. Such transient phenomena may be readily simulated. For example, a sharp tap delivered to the skin over the radius at the wrist can produce a transient sound which may be subjectively indistinguishable from Korotkoff sounds (Fig. 3A).

**Changes in Frequency Content with "Muffling" of Korotkoff Sounds**

Diastolic pressure is most consistently signaled by an abrupt change in the character of Korotkoff sounds ("muffling") as cuff pressure descends below this critical level (21, 25).

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**FIGURE 4**

The transcutaneous Doppler flow detector generates a beam of 5 Mcycle/sec ultrasound passing through the skin and the underlying artery. Some of this ultrasound is backscattered from acoustic interfaces such as vascular walls and erythrocytes. Ultrasound backscattered from stationary structures undergoes no change in frequency. If the structures or particles are moving, a Doppler shift occurs which is a function of the mean velocity of the particles making up the interface.
The nature of the changes in frequency content of the initial transient component of the Korotkoff sounds just above and just below this level was studied by spectral analysis (26).

An Altec-Lansing capacitance microphone (Model 165A) was coupled to a Littman stethoscope head positioned over the brachial artery in the antecubital fossa of 9 human subjects. Records were made of the sound preceding muffling, the muffled sound, and the sound following muffling. The sound waveforms were displayed on an oscilloscope (Tektronix Model 535) and photographed (Grass Camera Model C4). The film records of the Korotkoff sound waves were transcribed onto a photoformer function generator which produced a repetitive waveform for analysis. The frequency spectra of the sound waveforms were obtained from a wave analyzer (Hewlett-Packard Model 302A). The results are shown in Figure 3B. Above diastole, the frequency spectrum of the Korotkoff sounds extended to 180 cycle/sec. At diastole and below, the frequencies between 60 and 180 cycle/sec became markedly attenuated. Attenuation of the higher frequency components in the initial transient vibrations apparently represents the phenomenon called “muffling” with or without persistence of the “compression murmur” at cuff pressures below the diastolic level.

**Flow Velocity and Arterial Wall Movements in the Genesis of Korotkoff Sounds**

The various concepts regarding the genesis of Korotkoff sounds can be classified into two main groups: Disturbances originating in the fluid (i.e. eddies, turbulence and cavitation) and displacements, pulses or oscillations of the arterial wall below the cuff. The relative roles of these two mechanisms can be evaluated only by techniques which selectively respond to arterial wall motion and blood-flow velocities. The recently developed transcutaneous Doppler flow-detection equipment (27-29) provided an opportunity to make this type of distinction in human subjects without hazard or disturbance of the artery in its normal environment.

The transcutaneous Doppler flow detector,
illustrated in Figure 4, has been described in detail elsewhere (27-29) with a critical appraisal of its applications and limitations (29). This device appears to have particular value in the study of Korotkoff sounds because the differentiated signal produced a deflection related to the blood-flow velocity in the underlying vessel. The signal-amplitude waveform appears to be affected by arterial wall movements (see Figs. 5B, 6).

A special ultrasonic transducer (2 cm long, 1 cm wide, and 0.5 cm thick), a standard adult cuff, and a Ling-Temco-Vought microphone (LTV-3) were placed on one arm of supine, resting subjects (Fig. 5). Transducers were positioned over the brachial artery in three sites: 2 cm above the upper cuff margin, under the cuff, or 2 cm distal to the lower cuff margin. Frequently two Doppler systems were used simultaneously to detect temporal relations (Fig. 5). The cuff was cycled with a standardized inflation-deflation system utilizing compressed air and semiautomatic solenoid valves. Cuff pressure was monitored with a Statham P 23AA strain gauge manometer. An observer listened to the microphone output and marked the record at systole, muffling, and cessation of the Korotkoff sounds. The recordings were made on either a Sanborn recorder (model 850) or a Honeywell Visicorder (Model 1108). Timing relationships were determined from recordings at paper speeds of 100 or 200 mm/sec.

The delay in the display of signal amplitude was less than 1 msec; the delay in the display of the differentiated shifted frequencies was

![Figure 6](https://example.com/figure6.png)

**FIGURE 6**

The relationship between changes in cuff pressure, Doppler signal amplitude and the Korotkoff sounds. A typical complete cycle is included above the high speed samples from systole and diastole. The large amplitude, low frequency signals (arrows) are synchronous with Korotkoff sounds. Such spikes are typical of the signal from an arterial wall or similar acoustic interface of large area. The Korotkoff sounds were retraced to improve photographic clarity.
20 msec as a result of a 15-cycle low-pass filter used to smooth the differentiator-rectifier output (Fig. 4). This delay was subtracted in determination of the results.

Simultaneous recordings were obtained during 259 cuff deflations in 14 subjects. With the unpressurized cuff, the flow-velocity waveform recorded 2 cm above the upper cuff margin began slightly in advance of the velocity waveform recorded from a transducer positioned under the cuff (Fig. 5). This delay was computed to represent a local group or pulse wave velocity ranging about 6 m/sec, agreeing with previously published values (16). The signal-amplitude recordings demonstrated relatively flat backscattering levels during flow and none between flow periods due in part to attenuation of low frequencies (below 200 cycle/sec) by the Doppler receiver filter. No Korotkoff sounds appear on the record with the cuff deflated (Fig. 5A).

With the cuff inflated to a point midway between systolic and diastolic pressure, the proximal flow-velocity records displayed a large systolic deflection with notching near the top, and sometimes two secondary deflections of flow occurred during long diastolic intervals (Fig. 5B). The waveform of flow velocity from the transducer under the inflated cuff often had a convex inflection on the upstroke. The systolic flow pattern was prolonged and lacked secondary deflections during the diastolic phase. The foot-to-foot time between the two flow-velocity waveforms was considerably increased as though the propagation velocity were greatly slowed by cuff inflation as described by Landowne (30) and by Anliker and Raman (16). The foot-to-foot velocity did not return to control values and the flow-velocity waveforms did not return to control height or configuration until cuff pressure descended well below diastolic pressure, as though the artery under the cuff were partially compressed even though it remained patent throughout the cycle.

The signal amplitude from the proximal transducer was only slightly changed by cuff inflation, but the signal amplitude from the transducer under the cuff displayed a very tall sharp spike. This spike was coincident with the recorded Korotkoff sound and with the very earliest deviation of the flow-velocity record from the baseline. Previous experience has indicated that tall signal-amplitude spikes which are not manifest on the velocity record represent low velocity displacement of sur-

![Figure 7](http://circres.ahajournals.org/)

**Figure 7**

Effect of reactive hyperemia. The high flow velocity is sustained throughout cuff decompression. Continuous flow coincides with sound muffling. Note persistence of the higher frequency, low amplitude portion of the signal after muffling has occurred. The Korotkoff sounds were retraced to improve photographic clarity.
faces rather than particles. Relatively low velocity, large amplitude, pulsatile movements of arterial walls or intervening fascial planes have been observed to produce tall spikes like those in Figures 5, 6, and 7. The Korotkoff sounds and signal-amplitude spikes were coincident in time and persisted for progressively longer intervals as cuff pressure declined. These murmur-like sounds may well be associated with disturbances in blood flowing under the cuff.

Typical relationships between the cuff pressure, the signal-amplitude spike and Korotkoff sounds are illustrated in Figure 6. The first Korotkoff sound which signaled systolic pressure occurred at about 124 mm Hg and was coincident with a small signal-amplitude deflection. The signal-amplitude spike and the Korotkoff sound attained very high amplitude by the third and fourth cycles and remained at high levels until cuff pressure approached diastolic pressure. The sound-amplitude deflection became prolonged after the initial spike, apparently representing persistence of flow under the cuff as the artery remained open for a longer and longer portion of the cardiac cycle. Sudden attenuation or disappearance of the initial amplitude spike was often but not always coincident in time with the reduced amplitude or muffling of the Korotkoff sounds. 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.

The flow-velocity patterns displayed no consistent recognizable change in form as cuff pressure passed through the level of diastolic pressure except under conditions of extreme vasodilation (i.e., reactive hyperemia). In 3 subjects the cuff was inflated above systolic pressure for 4 min to induce reactive hyperemia. As the cuff pressure approached diastolic pressure levels, the flow records reached zero near the end of each cardiac cycle. As the diastolic pressure level was reached, the flow at the end of diastole remained slightly above zero (see arrow in Fig. 7), and the Korotkoff sounds became muffled. As cuff pressure descended further, the flow under the cuff was well above zero throughout each successive cycle. These results provided direct evidence that the artery first remains open throughout the entire cardiac cycle when the cuff pressure descends below the pressure level at which muffling occurs.

Auscultatory gaps were induced in 3 subjects by Valsalva maneuvers performed while the cuff pressure was held midway between systolic and diastolic pressures. The disappearance of the Korotkoff sounds was consistently associated with disappearance of Doppler signals and they reappeared together in all cases.

Conclusions

1. In his original description, Korotkoff described at least two types of sounds in an artery just below a sphygmomanometer cuff inflated to pressures between systole and diastole.

2. Thus, Korotkoff sounds should be divided into at least two distinct components, an initial sharp tapping sound accompanying the arrival of the pulse wave (K1), immediately followed by a low amplitude jet noise or compression murmur (K2).

3. When an inflated sphygmomanometer cuff is decompressed, the appearance of the K1 sound denotes the systolic pressure level. With a continuing decrease in cuff pressure the compression murmur appears, becoming louder and longer until the cuff pressure reaches diastolic pressure. At that point the initial transient sound drops out and leaves a “muffled” sound consisting of the murmur alone. Thus the initial transient sound is the criterion for both systolic and diastolic pressures.

4. Evidence has been presented that the initial tapping sound (K1) is due to an acceleration transient produced by abrupt arterial wall distension as a jet of blood surges under the cuff into the distal artery. The com-
pression sound ($K_r$) is most likely a noise produced by the turbulent jet distal to the compressed arterial segment.

5. The $K_t$ sound contains frequencies in the range between 60 and 180 cycle/sec but lacks dominant frequency patterns so that it can be easily simulated by sharply tapping the skin over the hand or wrist.

6. Canine arteries under a compression cuff are primarily tapered with markedly reduced circumference representing constriction of the arterial wall as the transmural pressure is decreased and the wall is unloaded.

7. Externally applied pressure produced collapse of rubber tubes into a binodal configuration which bore little relation to the changes in configuration in plastic casts of compressed canine forelimb arteries.

8. Studies of the genesis of Korotkoff sounds must clearly identify which component is being investigated, realizing that the appearance and disappearance of Ki are the criteria of sphygmomanometry and $K_r$ has little significance in this technique.

9. The origins of such vascular sounds should be studied under conditions closely approximating those occurring in man.

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