Artifacts in First and Second Sounds of the Phonocardiogram

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SUMMARY
Phonocardiographic instrumentation tests using a square wave of sound pressure reveal differentiation spikes at the output of a dynamic microphone and at the amplifier-filter during initial onset of the test pulse. When the pulse reaches the plateau level, ringing oscillations can be observed in the amplifier-filter combination. Microphone differentiation and filter ringing are also present at removal of the test pulse. These artifacts can be observed as a frequency distortion at the beginning and end of the first and second heart sounds in the normal phonocardiogram. By observing the characteristics of these artifacts investigators and clinicians may be assisted in improving their understanding of heart sound recordings. It is suggested that clinicians use the square wave test to determine the distortion unique to their equipment.

Additional Indexing Words:
Heart sounds Differentiation
Instrumentation Ringing
Fidelity Phonocardiography

The phonocardiogram may be considered the visual written record of the mechanical vibration of the heart. Whether or not the recording is a faithful visual image of the original vibrations or what the observer hears depending upon the design characteristics of the instrumentation system. It would be prudent to assume that the recording is not a faithful visual image of the original vibrations or what one hears because the eye discerns spatial distance in a linear relationship and the ear detects sound intensity in a logarithmical relationship and has a nonlinear sensitivity to frequency. Also, the instrumentation, microphone, amplifier, filters and write-out have nonlinear characteristics of sensitivity, frequency response, and overload distortion qualities. Thus knowing these concepts, one comes to consider the visual written record of heart sounds as an aid to heart studies but not a faithful visual image of the original sound because the instrumentation may fail to detect some sound features, accentuate other characteristics, and add artifacts to the record that are not in the original sound. These deficient qualities of phonocardiographic equipment are known to investigators: lack of microphone low-frequency response and sensitivity, nonlogarithmic intensity recording, and artifact signals added by filters.

The purpose of this investigation was to demonstrate by simple test artifacts in phonocardiographic recordings caused by characteristics of the instrumentation system using dynamic microphones and band pass filters. Thus investigators would be alerted not to ascribe physiological functioning to some recorded squiggle that was an artifact of the instrumentation, and clinicians would learn that some of the oscillations they see in clinical records have no pathological significance.

Methods and Equipment

The response of a system to a step function or square wave input was considered an appropriate approach. The square wave may be simply generated, and the method determines low-frequency, high-frequency, and transient response from a single simple pulse. A square wave of energy, either electrical or sound, is generated and applied to the input of the system under test and the output of the system is then recorded. By observing the difference between the known input and recorded output, one can obtain a measure of the distortion caused by the system. A square wave should go from one signal level to another signal level, maintain a fixed level for a given time, and then return to the initial level. By determining the time required for the system to change from the lower level to the higher level, one can determine a measure of the response to higher frequencies and by observing how the fixed level or plateau is sustained, a measure of the response to low frequencies can be determined. Naturally, if there are characteristics in the recorded signal that are not in the original signal, these are artifacts produced by the instrumentation system.

Figure 1 displays a simple method and instrumentation used to square wave test phonocardiographic equipment. A 6 volt battery potential is pulsed on and off by switch S. This potential is applied to the voice coil of a small speaker through a 10,000 ohm attenuating potentiometer. A 50 microfarad capacitor has been placed across the voice coil to...
provide critical damping of the speaker cone thus eliminating any ringing effect in the speaker. With a DC potential across the voice coil the speaker cone deflects and maintains a displacement as long as the voltage is applied. When the applied potential is removed, the voice coil returns to its resting position. A pulse of mechanical or sound energy is thus generated by an electrical pulse and communicated via a small plastic cylinder and 40 mm disc to the heart sound microphone. A flexible air tight diaphragm has been provided the 50 mm bell on the microphone by placing a condom over the bell opening.

The dynamic microphone was used because this type is very common in clinical phonocardiographic laboratories. Crystal microphones can also distort the incident sound if they do not respond to the low frequency component of heart sounds. The output of the dynamic microphone Hewlett-Packard Model 62-1500-C10 is fed through the impedance matching transformer to a Hewlett-Packard Model 350-1700B heart sound preamplifier. The dynamic microphone is made by attaching a coil of wire to a diaphragm and then the coil is placed in the field of a permanent magnet. To generate an output the coil must be moving in the magnetic field, hence the dynamic microphone generates a signal proportional to the velocity of movement. No velocity, no signal: thus there is only signal generated during the rise and fall of a pulse input and none generated during the plateau period of a pulse. To detect the low-frequency components in heart sound (0.1 to 100 Hz), a latex tube is connected from the bell of the dynamic microphone to a crystal microphone, Hewlett-Packard 374. Crystals have the property of generating an electrical potential when pressure is applied to bend them. Hence a constant pressure, a constant output, and the plateau period of a pulse input can be reproduced. Amplifier input resistance has a tendency to drain off the charge on crystals and the result is that even a crystal microphone cannot reproduce a long (greater than 10 sec) pulse plateau unless special charge amplifier techniques are used. The crystal microphone output is applied to the AC input of a Hewlett-Packard 350-5200A electrocardiogram (ECG) amplifier.

The electrical pulse that is applied to the speaker coil, and the output from the dynamic and crystal microphone amplifiers are viewed and photographed on a multitrace storage oscilloscope, Tektronix 5103N.

Results of Pulse Testing

Figure 2 displays three electrical waveforms associated with square wave testing of the dynamic microphone without its associated heart sound amplifier. The lower waveform is the electrical input to the speaker that generates a sound pressure pulse. The damping effect of the 50µF condenser can be observed as a curve that connects the leading edge to the flat top and the trailing edge to the base line. The pulse duration is 100 msec. The middle trace is from the crystal microphone and its associated amplifier. This waveform confirms that a square wave of sound pressure has been generated and applied to the dynamic microphone. The top of this waveform tilts and is not totally flat like the electrical pulse that generated it. This demonstrates that the crystal system would not provide a continuous output. In general terms the crystal system does reproduce the input signal with a minimum of distortion. The upper trace in figure 2 is the related signal generated by the dynamic microphone. The amplitude of deflection of crystal and dynamic amplifiers was adjusted so that normal heart sounds produced a deflection of one divi-

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**Figure 1**

Method of square wave testing phonocardiographic instrumentation.
sion, the same as that shown in figure 2. The electrical input to the speaker pulse generator was adjusted to cause this one division deflection. This assured that tests made on the system would be in the sound pressure level range of normal heart sounds. For this test the output of the dynamic microphone and matching transformer was applied directly to a DC to 1000 Hz differential amplifier on the oscilloscope. This permitted measurement of the microphone only and not the additional effects of characteristics in the heart sound amplifier.

The upper trace in figure 2 is the electrical output from the dynamic microphone and is the classic waveform of differentiation of a square wave signal by an energy storage device, the time constant or frequency response characteristics of which have not been matched to characteristics of the input signal. The waveform consists of positive and negative sawtooth-like deflections. The positive is generated when the pressure pulse is applied and the coil of the microphone is moved to cut lines of force in the magnetic field; after the displacement has stabilized, the movement of the coil ceases and the microphone voltage returns to zero following an exponential-like curve. When the pressure pulse is removed, the microphone coil again moves but in the opposite direction generating a negative voltage. As the displacement signal returns to its base line, the coil ceases to move and the negative potential decays in an exponential manner to the base line. Thus a single sound pulse of 100 msec duration can generate positive and negative sawtooth-like wave forms in a dynamic microphone. This has importance in heart sound recording for if the true heart sounds have frequency components that are both within and lower than the response characteristics of the microphone, extraneous signals will be produced when the microphone signal returns to its base line during periods when the heart sounds are lower in frequency than the response characteristics of the microphone.

To observe characteristics of the heart sound amplifier independent of the microphone, an electrical square wave was generated and applied to the amplifier input. Again the six volt battery was used. A voltage divider was made by placing a 47,000 ohm resistor in series with a 10,000 ohm potentiometer. The output taken across the potentiometer, swipes and ground was adjusted to provide a 20 mV signal, about the same voltage generated by the dynamic microphone with normal heart sounds. A switch was used to pulse the 20 mV test signal on and off. The amplifier, a Hewlett-Packard Model 350-1700B, was set with the filter slope in the 24DB/octave position and lower filter cut-off frequency in the 25 Hz position. The gain control was set to the midposition. Output was taken across the accessory terminals and applied to a DC amplifier in the oscilloscope.

Figure 3 displays in the lower trace the 20 mV, 100 msec square wave applied to the amplifier input. The upper trace in figure 3 displays the output of the amplifier.

The amplifier output waveform displays a differentiation with ringing. Again the reader is referred to the work of Van Vollenhoven et al. and a direct quote

![Figure 2](image1.png)

Waveforms associated with square wave testing of dynamic microphone (lower) electrical input to speaker, (middle) speaker generated pulse of sound pressure applied to microphone, and (upper) electrical output of microphone showing differentiation of the square wave sound input. The pulse duration is 100 msec.

![Figure 3](image2.png)

Response of heart sound amplifier (upper) displaying differentiation and ringing when square wave (lower) electrical signal with an amplitude of 20 mV and duration of 100 msec is applied to input. The filter slope is 24 DB/octave and lower cut-off frequency is 25 Hz.
from Tavel,6 "When one feeds an abrupt burst of sound into a filter (transient response) it will not only reproduce the input signal, it will also distort this signal and may produce artificial pre- and after-vibrations." The upper trace in figure 3 demonstrates this phenomenon, only the input waveform has not been reproduced. The "pre-vibrations" occur at the leading and trailing edge of the input test pulse and are the result of capacitor charging currents in the amplifier and associated filter. The three overshoot peaks that occur after the main spikes have returned to the base line are the result of ringing in the filter. Thus with a single pulse into the amplifier it is possible to generate an output waveform with eight distinct peaks, four at the start and four at the end, which does not look much like the input waveform. Raising the cutoff frequency of the amplifier filter had a tendency to generate the same number of peaks in the output waveform but decrease the time interval between peaks. Filters having different slope characteristics, and band width features would naturally have different ringing characteristics.

To observe the response of the total system (microphone plus amplifier), the method outlined in figure 1 was followed. Figure 4 displays the associated waveforms. The lower trace is the electrical square wave that is applied to the speaker coil. The middle trace is the electrical signal detected by the pulse microphone and amplified by the ECG amplifier. This again demonstrates that a sound pressure pulse has been generated and applied to the bell of the dynamic microphone. The upper trace displays the electrical output of the microphone plus amplifier. The amplitude of the driving pulse was adjusted by R1 so that the height of deflection in the upper trace (microphone plus amplifier) was the same as produced by normal heart sounds.

The upper waveform in figure 4 is much like the upper waveform in figure 3. There is little difference between the amplifier alone and the amplifier plus microphone in the response to a square wave input pulse of 100 msec. The leading edge of the sound pressure pulse causes the microphone to generate a spike of voltage that is differentiated in the amplifier filter combination resulting in an initial sharp spike (pre-vibrations). Ringing in the filter (aftervibrations) provides the three following exponentially decaying peaks. During the plateau time or low frequency phase of the test pulse there is no output. At the return to base line of the test pulse a similar complex of oscillations are also observed but reversed in polarity. Thus, due to differentiation and ringing, a frequency distortion can occur in phonocardiographic instrumentation that transforms a pulse having one peak into a complex of oscillations that has eight peaks and does not resemble the input signal.

Results With Heart Sounds

When the characteristics of extraneous signals (artifacts) generated by the instrumentation are known, it may be possible to identify them in the final written record. Figure 5 displays heart sounds and the apexcardiogram recorded via the same chest piece. The sounds were recorded with the dynamic microphone in a clinical manner with the filter slope set at 24 DB/octave and the lower cut-off frequency at 25 Hertz. The waveform of the apexcardiogram was recorded on equipment with a measured time constant of 0.635 sec and confirms that a pulse of sound

![Figure 4](image_url)

(Upper) Response of dynamic microphone plus amplifier-filter showing differentiation and ringing at beginning and end of a square wave of pressure. (Middle) Sound pressure pulse applied to dynamic microphone as measured with model 374 crystal microphone. (Lower) Electrical square wave applied to speaker to generate sound pressure pulse.

![Figure 5](image_url)

Phonocardiogram (upper) with associated apexcardiogram (lower). Biphasic differentiation spikes can be observed at beginning of first and second sounds with filter ringing at the end of each sound.
pressure has been generated and is incident in the bell of the dynamic microphone. The width of the apex pulse is approximately 320 msec and has a rise time of 50 msec. Initially at the first heart sound, there is a biphasic oscillation, and this occurs at the leading edge of the apex pulse. It is the result of differentiation of the first segment of the leading edge of the apex pulse with the fastest rise time. There are two inflection points in the leading edge that result in two small peaks after the biphasic complex. Continued differentiation of the segment of the apex pulse from the second inflection point to the peak produces a peak in the phonocardiogram that has a rather ragged top. The last negative and positive peaks are the result of ringing in the amplifier and filter. The time interval associated with the formation of the last two peaks is 44 msec or a frequency of approximately 23 Hz. This frequency is clearly within the band pass capabilities (0.3 to 60 Hz) of the 374 pulse crystal transducer. The fact that these latter oscillations of the first sound are not observed in the apexcardiogram tends to confirm their artifactitious nature. During the plateau period of the apex pulse there are no frequency components that cause the dynamic microphone to generate an output and hence no differentiation or ringing. At the second heart sound there is again a biphasic oscillation but reversed in phase compared to the first sound. This is generated by differentiation of the fast decay component of the training edge of the apex pulse. There is only one, barely discernible, inflection point in the trailing edge with no observable effect in the second sound. Again after the biphasic spike as in the first sound, there is a positive-negative-positive complex with the same time duration or frequency. This again is the result of ringing in the filter.

Figure 6 is an enlarged view of the first and second sounds recorded with the subject in a supine position. Each sound can be divided into two parts, "A" and "B." The "A" parts of each sound consist of oscillations related to differentiation and the "B" parts to ringing. The "A" part of the first sound has more peaks than the "A" part of the second sound. This suggests that there are more inflections occurring in the true vibratory motion of the heart during the first part of the first sound than during the first part of the second sound. It has been observed that, sometimes during the first part of the first sound, the ringing phenomenon will start and a differentiation wave will occur and beat or mix with it, producing a null or gap in this area. Again, this suggests inflections in the pure heart vibrations during the first part of the first sound.

**Discussion**

It has been demonstrated that a dynamic microphone and the input characteristics of amplifiers and filters can result in electrical differentiation of mechanical or sound energy producing spike-like waves at the initial input of the signal. Electrical filters ring and thus continue to provide a signal after an input has been removed. These two phenomena, differentiation and ringing, occur at the beginning and end of an abrupt signal input. In phonocardiograph recordings the first and second heart sounds appear as distinct entities and differentiation and ringing can be observed at the beginning and end of each sound. The sound or mechanical energy pulse used to test for these phenomena had a rise time of 6 msec, a duration of 100 msec and it took 1.56 sec to decay to zero. Using Schoenfeld's method for evaluation by square wave response, the pulse provided a test signal that would be reduced 30% from a sine wave signal in the range 0.1 to 28 Hz. This test signal was in the range to favor detection of extraneous signals produced in phonocardiographic instrumentation and well within the range of normal precordial vibrations. This permitted identification of artifact components in normal heart sounds. Naturally, different types of microphones with differing frequency response characteristics will produce somewhat modified differentiation spikes; also, filters with different slope and band pass characteristics will produce slightly different ringing patterns.

It is suggested that clinicians test their equipment with a square wave in the following way to determine its unique artifact generating characteristics: place a rubber cover over the microphone bell forming an air tight seal; gently apply and release pressure on the diaphragm. This is a very gross test, yet differentiation and ringing may be observed. Naturally, a more controlled application and release of pressure would provide higher quality results.

Recording from various locations in the precordial

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Figure 6

Normal phonocardiogram recorded in supine position with lower filter cut off at 25 Hz. The "A" sections of the first and second sounds display area of differentiation with inflections in sound pressure producing multiple differentiation spikes. The "B" sections display filter ringing.
ARTIFACTS IN THE PHONOCARDIOGRAM

area should modify the differentiation artifact. Thus the greater the displacement or more pulsatile the sound energy, as in the apex area, the greater will be the differentiation spikes; similarly differentiation at the sternum should be minimized. Yet, regardless of the location, when the incident sound is complex, containing components within and lower in frequency than that of the response of the microphone, differentiation will result.

Using current equipment — microphones that do not respond to frequencies below 20 Hz and band pass filters — it is nearly impossible to record an artifact-free phonocardiogram. Yet it is true that there are frequency components in heart sounds that are detected and displayed by phonocardiographic instrumentation with a minimum of distortion. Murmurs are in this category. Despite the fact that there are known artifacts in heart sounds, valuable diagnostic information can be obtained: the timing of the first and second sound complexes in relation to other cardiac events, the duration of the envelopes, and especially the appearance of signals where there should be no signals and differences from established normal patterns all yield information of clinical value. The phonocardiogram can be a very valuable instrumentation technique despite the mentioned artifacts.

References

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