

Stethoscope Acoustics

I. The Doctor and His Stethoscope

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IT is an anachronism that the stethoscope, introduced in 1819, remains an indispensable medical tool today although no standards have ever been set for its acoustical performance.¹ Neither has a standard test been established for evaluating the acoustics of the intact instrument. Furthermore, there is no information on the intimate acoustical interaction of the stethoscope with the doctors' ears.²

Our initial approach to these problems was to adapt an already established technique of testing insert-type earphones^{3, 4} (hearing-aid types) to the testing of stethoscopes which are also acoustical devices of insert type. A deficiency in the method is its exclusion of human ears at the stethoscope earpiece. Since any stethoscope has little utility in the absence of a human listener, a fundamentally different test method was devised in our laboratory which does include the acoustics of human ears in testing the acoustics of stethoscopes.

This paper presents an evaluation of both objective test methods. Good agreement has been attained between the objective frequency response curves of the second method and the results of subjective listening tests with the same stethoscopes. The acoustical interactions of human ears with stethoscopes are also delineated.

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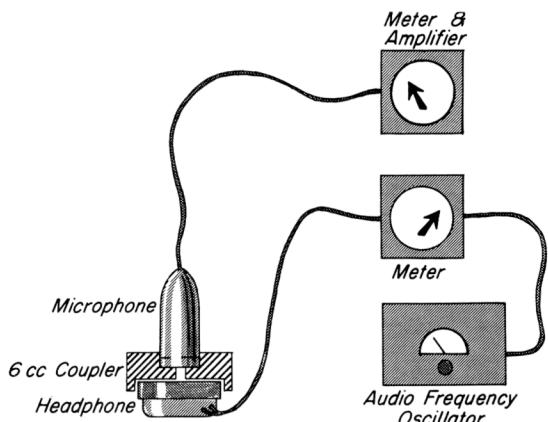
Method

Two separate test methods were set up to obtain the transmission acoustics of the same stethoscope (reference stethoscope was the Ford*). The two methods differed basically in the manner by which the sound source and the detecting microphones were coupled to the test stethoscope. Method A describes direct coupling (modified after the American Standards Association method). Method B describes indirect coupling (designed in our laboratory).

Method A (Objective)

A complete description of the original method is found in the American Standards Association method for coupler calibration of earphones.^{3, 4} In brief, a magnetic type headphone (earphone) was used for the sound source. It was first calibrated in a 6.0 cc standard coupler (fig. 1). The chestpiece of the stethoscope was then placed directly over the headphone end plate. There was no sound distortion due to chestpiece contact pressure. Each earpiece was inserted into one opening of a 2.0 cc standard coupler (fig. 2). Into one of the 2.0 cc couplers, a standard condenser microphone was inserted. The other coupler was sealed off, that is, it was a "dummy" coupler. Petroleum jelly seals assured air-tight contacts at both the earpiece and the chestpiece. Input voltage to the headphone was kept constant for both its calibration and for testing of the stethoscope. The assumption implicit in this method is that sound pressure measured in the calibration coupler is an approximate indication of the pressure developed by the source. Sound pressure at the stethoscope earpiece is compared with the pressure in the calibration coupler for the same source driving voltage. The ratio of

*Ford bell type. There are several models of Ford stethoscopes which differ both in design and in frequency response. The observed data relate to one model only.



METHOD A CALIBRATION OF SOUND SOURCE
Figure 1

Method A: oscillator generates pure-tone signals at constant voltage. First meter monitors driving voltage. Calibration coupler directs sound from headphone to detecting microphone. Microphone output is amplified and indicated on second voltmeter. Microphone output = P_1 in sound pressure ratio formula.

these pressures is expressed in decibel units (db):

$$\text{where } \text{db} = 20 \log_{10} P_2/P_1$$

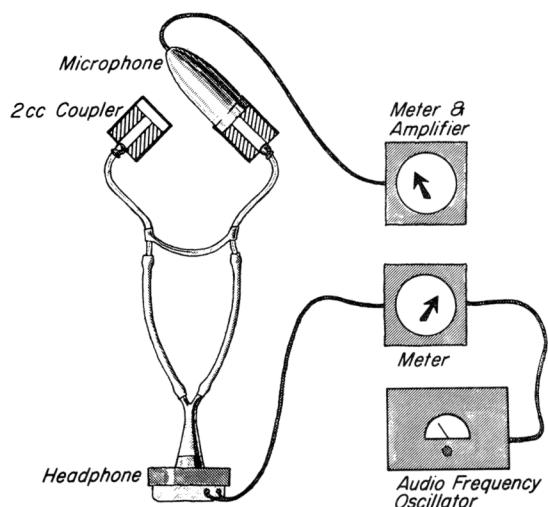
P_2 = sound pressure detected at stethoscope earpiece
 P_1 = sound pressure in the 6.0 cc calibration coupler.

The response curve of the reference stethoscope is plotted in decibels on log graph paper.

Method B (Objective)

A dynamic-type headphone was employed as the sound source in this system. It was clamped to a nonvibrating sound stage enclosing a 50 cc cavity (fig. 3). The stage had two identical 0.5 inch openings. One opening was fitted with a monitoring microphone.* The other opening permitted the passage of sound into the chestpiece of the stethoscope. This coupling permitted the direct measurement of source sound pressure at the input to the stethoscope chestpiece. It also eliminated sound damping attendant upon direct contact between the vibrating element of the sound source and the stethoscope chestpiece.

The headphone was driven by an amplitude-variable oscillator. The output of the monitoring microphone regulated the amplitude of oscillator output to a pre-set level through a compressor



METHOD A DIRECT COUPLING
Figure 2

Method A: by substitution, stethoscope replaces calibration coupler. Standard 2.0 cc coupler (on right) establishes continuity between detecting microphone and stethoscope earpiece. Dummy 2.0 cc coupler (on left) provides air-tight termination of other earpiece. Microphone output = P_2 in sound pressure ratio formula.

circuit. This formed a complete feedback control system assuring a constant sound pressure signal for each stethoscope tested (± 1 db). The sound source was thus made independent of varying acoustical loads presented by differing stethoscopes and human ears.

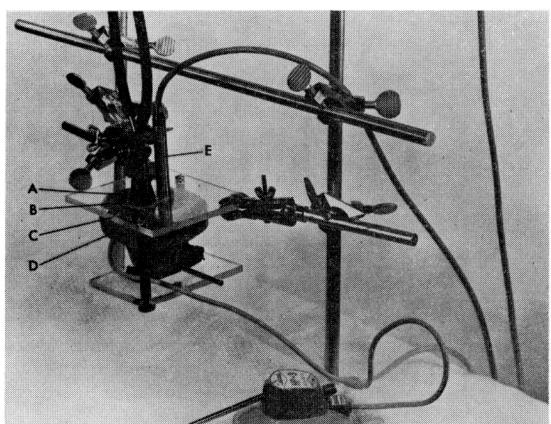


Figure 3

Method B: sound source apparatus. (A) Stethoscope bell; (B) petroleum jelly seal; (C) sound stage; (D) headphone source; and (E) input microphone.

*Condenser-type microphone, Brüel and Kjaer, Model 3141. This instrument is sensitive to sound pressure per se, and fully calibrated by the manufacturer.

The sound output of the stethoscope was detected at the junction of its earpiece to the external auditory canal of the ear by a probe tube (2.0 mm I.D.*) inserted through a hole drilled into the tip of the earpiece (fig. 4 and insert fig. 5). The probe was connected to a microphone which was previously calibrated. The microphone-probe combination was then re-calibrated.⁵ The probe was found to modify the output of the microphone at certain frequencies. Therefore, a special filter was designed to compensate for, or to "normalize" the probe frequency distortion. The frequency characteristics of the filter were made inverse to probe characteristics. The two distortion curves canceled each other. The resulting microphone-probe response was then flat, ± 1.5 db 20 to 3,000 cps. It was determined that the presence of the small probe at the earpiece outlet did not perceptibly alter sound passing around it. The probe technique thus provided the means of measuring sound pressure at the critical earpiece-auditory canal junction without distortion. Airtight seals were achieved by using petroleum jelly as a sealant at the chestpiece end and well-fitting earpieces at the other end. A completely airtight system was electronically confirmed. The entire test system is diagrammatically summarized in figure 5.

Sound pressure levels of the input signal and the stethoscope output were automatically recorded on a graphic level recorder which was synchronized with the sweep-frequency oscillator. The entire system was fully calibrated in absolute units, expressed as decibels (relative to 0.0002 dyne/cm²). The decibel scale appears along the ordinate and test frequencies are indicated along the abscissa in all graphs presented. Tests were carried out in a soundproof, electrically shielded room and all electronic components, exclusive of the sound source and microphones, were installed outside the room (fig. 6).

Threshold Correlation Study (Subjective)

This subjective study was undertaken to discover whether a stethoscope changes the characteristics of the ear so as to alter threshold levels or changes the sound pressure of the input signal as it travels through the stethoscope. The study also provided the means of obtaining a subjective validity check upon the objective data from methods A and B.

Four subjects who had proven normal hearing and who were fully trained in the threshold measurement technique were studied. For each one, a frequency response curve was obtained with the reference stethoscope by method B. The

frequencies where amplification peaks and attenuation valleys occurred were taken as test points for hearing threshold determinations.

A Békésy audiometer,⁶ also calibrated in absolute units, was used for the threshold measurements. The apparatus consists of an oscillator coupled to a motor-driven attenuator activated by the subject (fig. 6, right). The pre-selected frequency was set on the oscillator with the sound signal delivered to the subject's ears through dynamic-type earphones.* The intensity of the

*Fedtro, model STR-H dynamic-type headphone. Dynamic-type headphones were used in this study because of their stable output in the presence of differing acoustical loading. Earphones of magnetic type were unsuitable because the acoustical impedances of normal human ears and of differing stethoscopes were found to alter their sound output despite constant driving voltages. An additional advantage of this ear-muff type of headphone is that it does not exert distracting pressure upon the pinna; the ear is thus unencumbered as in free air.

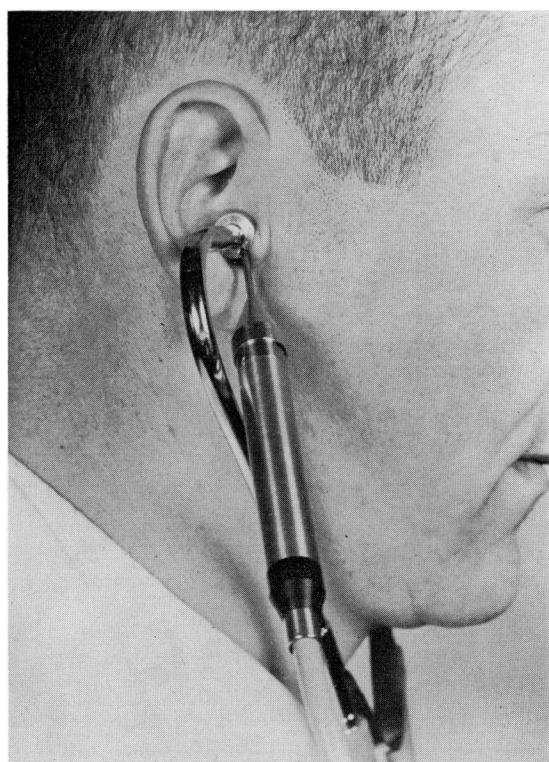
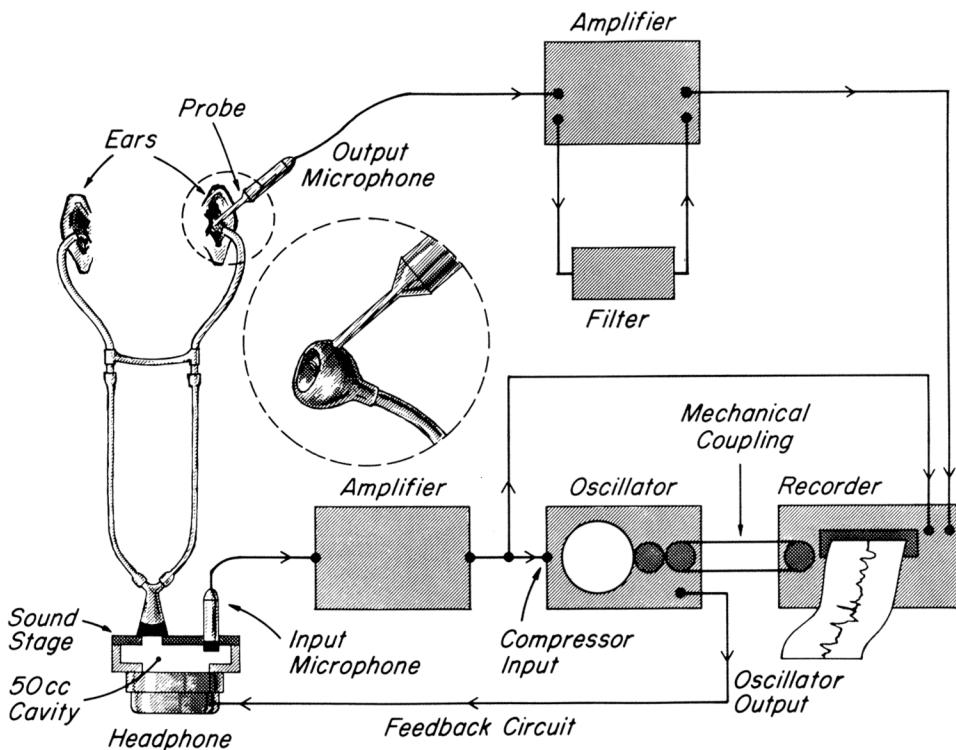


Figure 4

Method B: output measurement at ear. Reference stethoscope is worn in usual fashion. Probe couples directly to open diaphragm of output microphone. Probe tip is inserted through earpiece to junction with external auditory canal.

*Probe kit UA 0040, Brüel and Kjaer.



METHOD B INDIRECT COUPLING

Figure 5

Method B: diagrammatic summary.



Figure 6

Method B: electronic components. (Left to right) Graphic level recorder, synchronized oscillator-compressor unit, probe normalizing filter (foreground), amplifiers for input and output microphones (background), Békésy audiometer. Soundproof room is behind components.

signal automatically increased until it exceeded the observer's threshold and was heard. The subject then pressed a switch which reversed the attenuator decreasing the sound signal until it was no longer heard. At this point, the subject released the switch allowing the signal, once again, to rise above his threshold. A synchronized pen recorded the attenuator positions. The midpoint between the extremes of attenuator sweep was taken as the threshold level. The sound pressure at threshold was directly measured in the narrow space between the headphone and the ear by the probe technique. This procedure was repeated at each test frequency.

The headphones were then removed from the subject and the reference stethoscope was interposed between the listener's ears and the headphone. New threshold levels were obtained at each test frequency. Sound pressures at threshold were again measured at the ear and additional measurements were made at the headphone beneath the stethoscope chestpiece. The two sets

of data permit a comparison of threshold sound pressures at both the source and the ear with and without the stethoscope.

Human Response Variations (Objective)

Some variations in the response of the reference stethoscope were observed when it was worn by the four individuals in the preceding study. Since there were neither variations in the input signal nor any alterations of the stethoscope itself, this variance reflected acoustical differences in the ears of those wearing the stethoscope. The range of variation in this response was assessed in a series of subjects wearing the reference stethoscope.

The frequency response of the reference stethoscope was obtained for each subject as described in method B. Forty response curves were obtained on 20 subjects; 10 were tested once, and 10 were tested on three occasions each. The number of subjects tested exceeded the recommendations of the American Standards Association for the testing of individuals wearing sound attenuator muffs.⁷ No such standard has, as yet, been established for the testing of individuals wearing stethoscopes. The larger series was thought necessary for adequate sampling for the following reasons: In addition to response variations among individuals, there are daily variations in the same individual, and there are also response variations related to age. The subjects' ages ranged from 22 to 62 years. All subjects were proven by clinical audiometry⁸ to have normal hearing within the pertinent frequency range.

Two subjects, not included in the normal series, were tested during and after recovery from acute upper respiratory infections. Combined studies were done on two additional subjects with clinical presbycusis.

Stethoscope Comparison Study (Objective-Subjective)

Frequency response curves and threshold measurements were obtained from the same subjects wearing two dissimilar stethoscopes. The techniques are the same as in the threshold correlation study. The purpose was to determine if differences in the objective response curves of acoustically differing instruments can actually be appreciated subjectively by experienced clinicians.

Results

Method A (Direct Coupling, Excludes Human Ears)

The frequency response of the reference stethoscope* as obtained by this method is

seen as the fluctuating curve in figure 7. The horizontal straight line at 0 db represents a condition where the sound pressure at the stethoscope earpiece is the same as the pressure in the calibration coupler. Positive-decibel values (above this line) indicate a pressure ratio greater than unity and negative-decibel values indicate a ratio less than unity. By this method, the characteristics of the frequency response of the reference stethoscope show a low-frequency "primary" peak at 130 cps. Additional peaks of lesser amplitude occur at 320, 500, and 700 cps. Also shown in figure 7 is the audibility pattern experienced by a subject wearing this instrument. Points of subjective amplification and attenuation are indicated by X's. There is poor correlation between the observed frequency response and the audibility pattern, especially at the frequency extremes.

Method B (Indirect Coupling, Includes Human Ears)

In this method, both the output and the input sound pressures are measured directly.

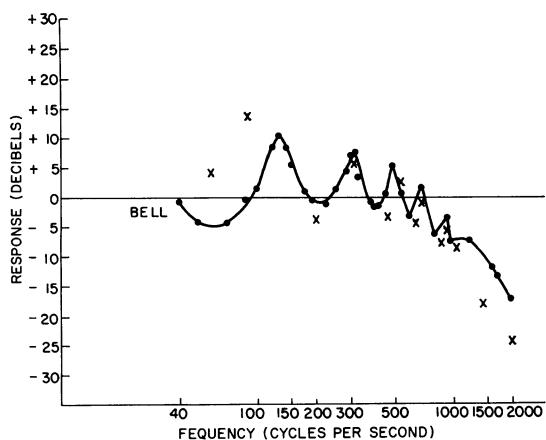


Figure 7

Method A: frequency response curve of reference stethoscope. Straight line at 0 db is the assumed "flat" response. Heavy-line curve is the measured response. X's show the audibility pattern experienced by a subject listening through reference stethoscope. There is poor correlation between the audibility pattern and the objective response curve by method A.

*Ford, shallow bell, Geo. P. Pilling & Son.

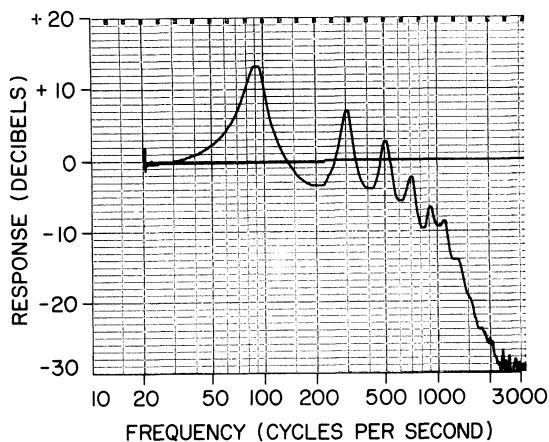


Figure 8

Method B: frequency response curve of reference stethoscope. Straight line at 0 db is the measured input signal. Fluctuating curve is the stethoscope output measured at subject's ear. This curve differs from that of method A in that the observed primary and secondary amplification peaks occur at lower frequencies, and a greater attenuation of the higher frequencies is apparent.

Figure 8 is a photograph of the actual recording of the normalized data taken off the graphic-level recorder. In this case, the straight line at 0 db is the measured input sound pressure in the cavity beneath the stethoscope chestpiece. When the stethoscope output, measured at the earpiece, exceeds the input measured at the chestpiece, true amplification has occurred, and the magnitude of this amplification is indicated in + db's. Conversely, attenuation is indicated by - db's. The frequency response curve of the reference stethoscope obtained by this method differs from the curve of the same instrument obtained by method A. The primary amplification peak occurs at 90 cps and the secondary peaks occur at 300 and 500 cps. Sharp, progressive attenuation occurs at 800 cps. It should be recalled that this curve was obtained with a human subject wearing the instrument. The curve is, therefore, a product of stethoscope acoustics combined with the acoustics of human ears.

Threshold Correlation Study

Threshold sound pressures, measured at the ear, were found to be the same whether the

subjects wore headphones or the stethoscope. The stethoscope did not alter the subject's hearing threshold. However, sound pressures required at the source to reach a subject's hearing threshold were found to be altered by the stethoscope and are indicated by closed circles in figure 9. Sound pressures required at the source to reach the hearing threshold with the subject wearing earphones is shown by open circles. The stethoscope reduced the source sound-pressure requirement at 90, 300, and 500 cps. Since threshold sound pressures at the ear were found to be undiminished, the lowered requirements at the source reflect amplification by the stethoscope. In mathematical terms, source sound pressure is inversely related to amplification. Therefore, an inverse plot of source sound pressure in this subjective study permits a direct comparison with amplification observed in the objective frequency response curve by method B. These data may be plotted on the same scale since both are expressed in absolute units. In figure 10, the frequency re-

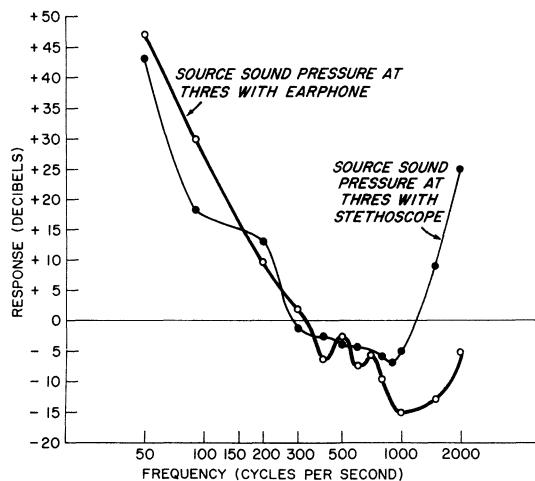


Figure 9

Source sound pressures at threshold. (Open circles) Hearing threshold curves, subject wearing earphones. (Closed circles) Source sound pressure, subject wearing stethoscope. The experimental endpoint was the achievement of sufficient sound pressure at the ear to reach the subject's hearing threshold (which is the same in either case). Thus, when less sound pressure is required of the source coupled to the stethoscope than when the source is placed directly against the ear, the stethoscope has amplified the original sound.

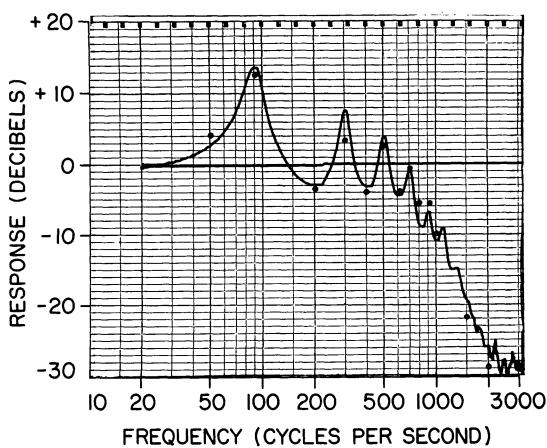


Figure 10

Method B: objective-subjective correlation. Straight line at 0 db is the measured input signal. Solid-line curve is the stethoscope output measured at subject's ear (same subject as figures 8 and 9). (Closed circles) Audibility pattern (inverse plot of source sound pressure differences fig. 9). There is good correlation between the audibility pattern and the objective response curve by method B.

Response curve of the reference stethoscope worn by the same subject is shown as the solid line. Superimposed on this curve and indicated by circles is the inverse plot of the source sound pressure required to reach his hearing threshold. The two correlate quantitatively and are well within the limits of experimental variation in the subjective technique. This same correlation between objective stethoscope response curves by method B and the subjective audibility data was verified in three additional subjects.

Human Response Variations (Objective)

The range of variations in the frequency response curve of the reference stethoscope when worn by 20 subjects is seen in figure 11. All of the individual curves are reproduced on the same graph. The extremes of individual differences are considerably less than the fluctuations caused by the stethoscope itself.

Younger subjects generally had greater amplitude responses, usually at higher frequencies, than did older subjects. Figure 12 compares the response of a medical student with a staff physician.

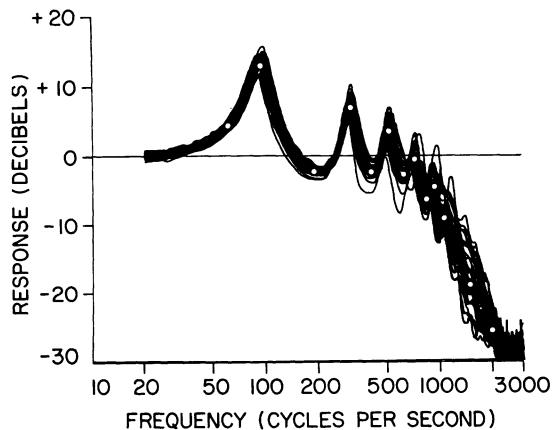


Figure 11

Average range of human ear response. Straight line at 0 db indicates input signal (± 0.5 db). Solid-line curves are composite of 40 response curves obtained on 20 normal subjects wearing the reference stethoscope. White dots show mean response at selected frequencies.

Response variations were occasionally seen when the reference stethoscope was tested against the same subject on successive days. Ten subjects were tested on three separate occasions. Figure 13 illustrates the greatest daily variations seen for any subject.

Two additional subjects (data not included in figure 11) were tested during and 2 weeks

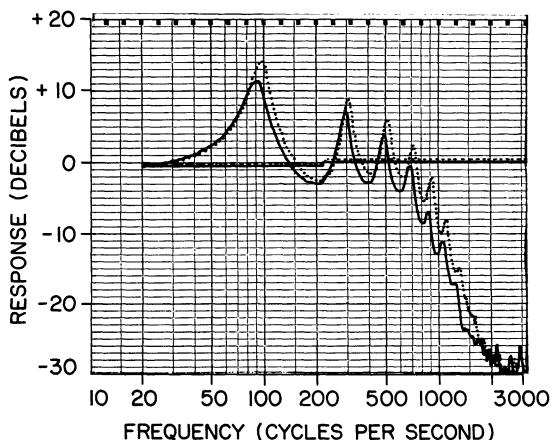


Figure 12

Response variations related to age. Solid line is the response of staff physician (age 36). Dotted line is the response of medical student (age 24). The medical student enjoys a slight acoustical advantage over his instructor.

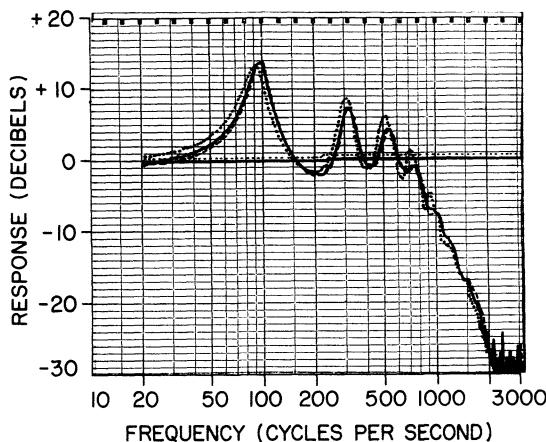


Figure 13

Individual response variations. The three curves were obtained on the same subject on three separate occasions. These represent the maximal daily variation observed in any of 10 individuals.

after recovery from acute coryza. Neither their audiograms nor their stethoscope response curves were significantly altered by their illness (fig. 14).

Stethoscope Comparison Study (Objective-Subjective)

Figure 15 compares the alterations in hearing threshold at high frequencies experienced by a clinician when wearing two dissimilar

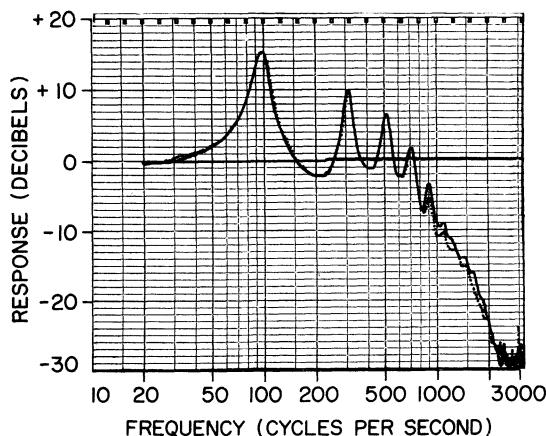


Figure 14

The effect of acute coryza on stethoscope response. Solid line is the response during symptoms of coryza. Dotted line is the response 2 weeks after recovery. This subject's response showed no significant variation due to the effects of an upper respiratory illness.

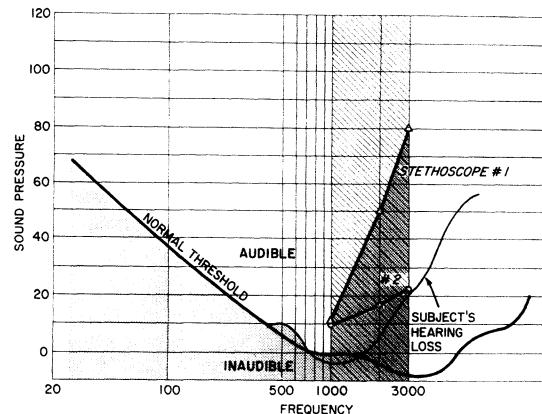


Figure 15

Effects of stethoscopes upon audibility. Heavy solid line is the normal hearing threshold. Light solid line shows the altered threshold of subject with presbycusis. (Triangles) Subjects' audibility with stethoscope no. 1. (Open circles) Subjects' audibility with stethoscope no. 2. The elevation of this subject's hearing threshold due to presbycusis has neither been compensated nor seriously worsened by stethoscope no. 2. Stethoscope no. 1, however, adds greatly to his hearing handicap.

stethoscopes. Senior clinicians were selected for this study. The example presented is that of a cardiologist whose audiogram showed marked hearing loss⁹ above 2,000 cps, which is indicated by the shaded area immediately above the normal threshold curve.

The source sound pressure required to reach this subject's hearing threshold with stethoscope no. 2 is indicated by circles at 1,000, 2,000, and 3,000 cps. Source sound pressure at threshold with stethoscope no. 1 is indicated by triangles at the same frequencies. The objective frequency response curve of stethoscope no. 2 showed an attenuation of 10 db at 1,000 cps, but was virtually flat at 2,000 and 3,000 cps. The subjective data in figure 15 are quantitatively similar. This instrument does not greatly add to the subject's already elevated hearing threshold nor does it compensate for the preexisting hearing loss through amplification. Stethoscope no. 1, the reference instrument, shows severe attenuation of high frequencies on the objective response curve. This stethoscope does greatly elevate the subject's threshold, accentuating his hearing loss.

due to presbycusis. Similar observations were made on these same stethoscopes by another senior clinician.

Discussion

The stethoscope is an acoustical instrument. How modern it is in appearance or how neatly it fits into the pocket are not to be equated with the acoustical performance of the instrument.¹⁰ Since surgery has increasingly entered into the management of cardiac patients, there has come with it increasing responsibility for accuracy in diagnostic evaluations¹¹ which include auscultation. The stethoscope often delivers the leading clue to the presence of complicating lesions associated with more obvious "primary" ones; for example, a ventricular septal defect with an associated patent ductus arteriosus. If the clinician uses a stethoscope which is acoustically deficient in the frequency spectrum of significant murmurs, he may miss the clue which would have led him to search for additional lesions at cardiac catheterization. Were the surgeon to be unprepared to handle these associated lesions, the operation may become complicated or disastrous. Clearly, more responsibility has been placed upon the diagnostician and his stethoscope in selecting the proper physiological studies for his patients.

The measure of stethoscope efficiency is an acoustical one. The test method by which stethoscope acoustics are measured should be designed to inform the clinician what he can and what he cannot hear when he wears the instrument. The clinician's ears were left out of test method A by the substitution of arbitrary, 2.0 cc couplers. It is not surprising, therefore, that this method failed to yield data related to what is heard.

Objective responses obtained by method B, which does include human ears, were quantitatively related to what clinicians heard through the same stethoscopes in subjective tests. Because both method B and the subjective audiometric technique were calibrated in absolute units, they served as a validity check upon each other.

Several design features are responsible for

the validity of method B. The sound source was made independent of stethoscope acoustics (impedance loading), and independent of force exerted upon the chestpiece (force effect). The input signal was held constant by the feedback system, was measured directly, and involved no assumed values. The observed "stethoscope acoustics" included the acoustics of human ears (impedance loading). The frequency response curves of stethoscopes were measured directly at the ear without distortion. The sound pressure response of a stethoscope measured at the ear is directly related to human audibility since the ear is sensitive to sound pressure per se.

Because method B incorporates all these prerequisites, it is applicable to studying the influence of ear acoustics upon stethoscope acoustics. The data from these studies are interpreted as follows:

1. Acoustical differences among the extremes of normal ear responses were real but relatively minor compared to the acoustical variations contributed by stethoscopes themselves.
2. Repeated testing of individuals with a given stethoscope showed inconsequential daily variations.
3. The clinician with uncomplicated coryza may be unaffected with respect to his acuity through a stethoscope.
4. A rather consistent but relatively minor variation in response was found associated with age differences. Younger subjects (medical students) tended to have better responses, especially at higher frequencies, than did older subjects (staff physicians). This removes any purely acoustical reasons why medical students may miss certain murmurs which are detected by their seniors, for example, the high-pitched murmur of aortic insufficiency. By the same token, senior clinicians may not necessarily be handicapped by presbycusis. This condition causes progressive deterioration of high-frequency acuity in most males past the age of puberty, but the hearing loss in most individuals occurs above 3,000 cps, which is also considerably above the useful frequency spectrum of a number of

stethoscopes. Also, it is yet to be proven that there are significant cardiovascular sound components above 3,000 cps. However, should a hearing loss extend downward, below perhaps 3,000 cps, clinical auscultation may be further handicapped by an inadequate stethoscope.

Objective frequency response curves indicated that the performance of one stethoscope can exceed another at the higher frequencies by more than 50 db. Subjective studies showed that physicians with presbycusis appreciated this difference. Sound intensities clearly audible to them through one stethoscope were totally inaudible through another. It would be an advantage for such clinicians to select a stethoscope which excels at high frequencies.

Controversy has long existed as to whether the mechanical stethoscope is capable of amplifying sound. Data from both the objective and the subjective studies indicate that it can amplify. However, amplification was found to be uneven in all instruments in which it did occur. The regularity of amplification peaks occurring through the test frequency range suggests that these peaks reflect standing waves within the lumen of the stethoscope. These occur when the length of a stethoscope matches quarter-wave lengths of the sounds passing through it. This results in reinforcement, commonly called "resonance peaks." Other factors may be involved, and specific studies must be carried out with instruments of constant length before this concept can be validated.

Summary and Conclusion

The objective test method described accurately defines the transmission acoustics of intact stethoscopes worn by human subjects. Mechanical stethoscopes possess uneven frequency responses, characterized by areas of

true amplification alternating with areas of sound attenuation in an undulating pattern. The acoustics of any stethoscope will reflect the acoustics of human ears when it is worn, but individual differences are small. Younger individuals usually enjoy slightly better responses to a stethoscope than do their elders. Large deficiencies in the response of a stethoscope at the higher frequencies add to the handicap of a clinician with presbycusis. The results of our objective test method correlate directly with what the clinician can and what he cannot hear through stethoscopes.

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