RESEARCH SUMMARY ON

CLINICAL ASSESSMENT OF PHYSICAL PARAMETERS ON MECHANICAL HEART VALVE SOUNDS

Hans Nygaard[1,2,3], J. Michael Hasenkam [1,2,3], Peter K. Paulsen[2], Jens Leding Kopp[1], Carsten Dollerup Jensen[1]

1. Department of Electronic Engineering, Engineering College of Aarhus.
2. Department of Thoracic and Cardiovascular Surgery, Skejby Sygehus, Aarhus University Hospital.
3. Institute of Experimental Clinical Research, Aarhus University, Denmark.

INTRODUCTION

It has been suggested that sounds produced by prosthetic heart valves reflect the structural and functional integrety of their components, and that early signs of valve failure should be visible in the spectra of the closing or opening sounds. However, factors in addition to the valve itself may influence the characteristics of precordial measured heart sound spectra.

Therefore, it is necessary to pick up the sounds at a point at the chest and during physical and physiological conditions, which gives the highest signal-to-noise ratio (S/N).

The purpose of the present study was to find the maximum S/N during measurements of precordial sounds from mechanical mitral valve prostheses in humans when changing the following parameters.

1. Measuring site: 1-9
2. Patient position: supine, left decubitus or prone.
3. Respiratory phase: inspiration or expiration.
4. Transducer type: B & K accelerometer or PCB pressure microphone

PATIENTS AND METHODS

Eight patients, 4 men and 4 women who underwent mitral valve replacement were investigated. They all had a St. Jude Medical bileaflet prosthesis implanted. After informed consent, interview, classic auscultation, heart rate and blood pressure recording, nine precordial measuring point were defined and marked according to figure 1.

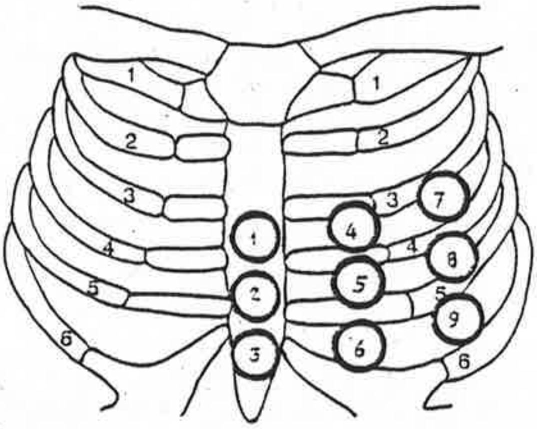


figure 1.

Heart sound measurements were performed in a small sound proof/anechoic chamber (3 x 4 m) with the patient in three different physical positions: supine, left decubitus and prone.

In order to perform precordial heart sound measurements with the patient in prone position the examination bed was equipped with a 30 x 30 cm hole and a corresponding shutter.

Heart sound measurements were performed over 10-15 heart cycles during calm spontanious respiration in all 9 precordial measureing point and repeated for the three physical patient position. Before changing position the same measurement series was made with two different transducer systems: 1) A sound pressure microphone (PCB piezotronics model 106M92) with a built-in preamplifier and a 1000 Hz high -pass filter. 2) A piezoelectric accelerometer (Brüel & Kjær, type 4371) equipped with a charge amplifier (Brüel & Kjær, type 2635).

Signal analysis was performed off-line using a commerciel signal analyzer (Brüel & Kjær, Dual Channel Signal Analyzer, type 2032).

The signal-to-noise ratio (S/N) was defined as the ratio between the energy of the two closing sounds E_s and the energy of the baseline noise E_n in diastole both calculated within a time window of 8 ms.

$$(S/N) = 10\log\frac{\frac{1}{T}\int_T v_s^2(t)\,dt}{\frac{1}{T}\int_T v_n^2(t)\,dt} = 10\log\frac{\int_T v_s^2(t)\,dt}{\int_T v_n^2(t)\,dt} = 10\log\frac{E_s}{E_n}\ (dB)$$

RESULTS

1. Measuring site

S/N was calcualted in all nine measuring points for the two transducer systems. In table 1 S/N for the best and second best measuring points are shown for all patients.

Table 1:

Patient no	Best/ second best, measuring points for PCB transducer			Best/second best measuring points for B & K transducer		
	supine	1.decub	prone	supine	1.decub	prone
F 1	6/8	6/5	9/8	3/9	7/3	5/8
F 2 (fat)	6/8	1/3	3/5	3/6	2/1	5/3
F 3	6/5	3/9	5/9	6/1	3/6	5/6
F4(skinny)	6/5	5/3	4/9	6/9	3/5	6/9
M 1	6/5	4/6	5/3	1/6	2/1	1/2
M 2	6/9	6/2	6/2	6/3	3/2	2/3
M3(skinny)	6/5	6/3	5/4	6/3	6/5	5/6
M 4(fat)	6/5	5/3	2/5	3/6	2/3	2/1
"Mean"	6/5	6/3	5/9	6/3	3/2	5/6

2. Patient position

Plots of the mean S/N for the four women and four men measured with the PCB and B & K transducers are shown for all nine measuring points in figure 2.

The three physical patient positions are plotted seperately.

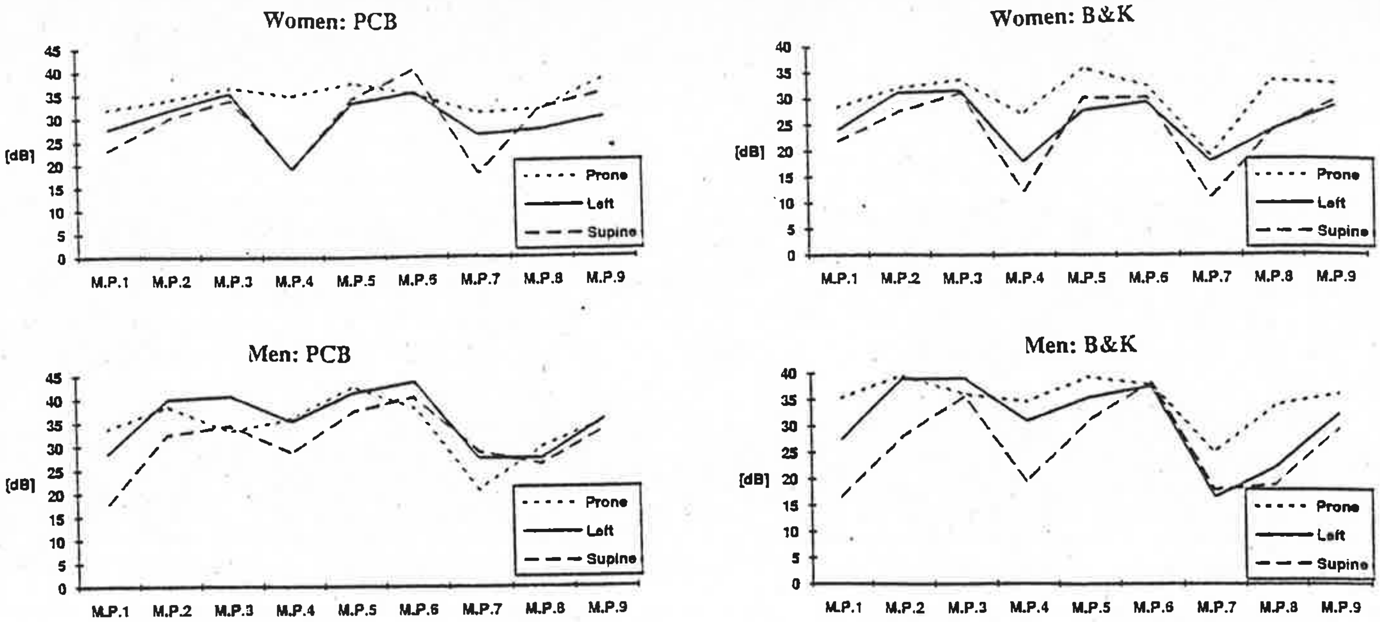
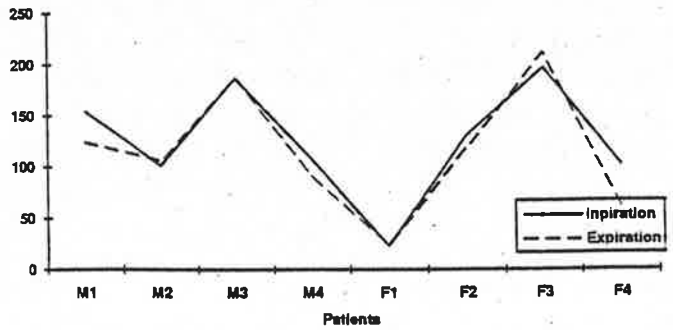


Figure 2

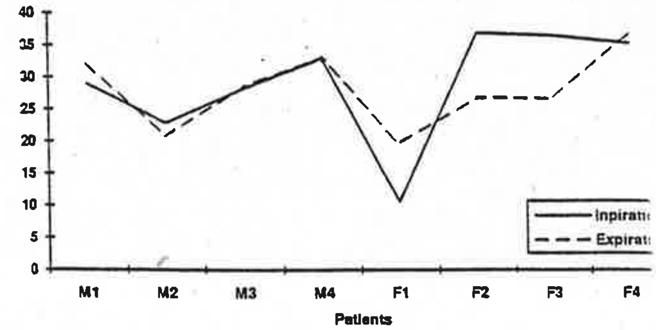
3. Respiratory phase

Peak-peak values of recorded closing sounds in measuring point 3 in respiratory inspiration and expiration phase are shown in figure 2 for all 8 patients in supine and prone positions measured with both transducer systems.

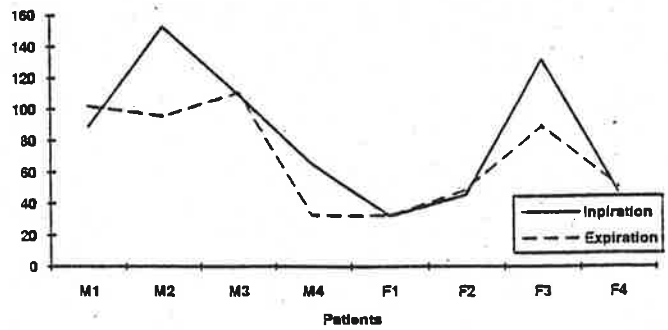
Prone position in M.P. 3 for women and men displayed in inpiration and expiration phase with B&K-transducer



Prone position in M.P.3 for women and men displayed in inpiration and expiration phase with PCB-transducer



Supine position in M.P.3 for women and men displayed in inpiration and expiration phase with B&K- transducer



Supine position in M.P.3 for women and men displayed in inpiration and expiration phase with PCB-transducer

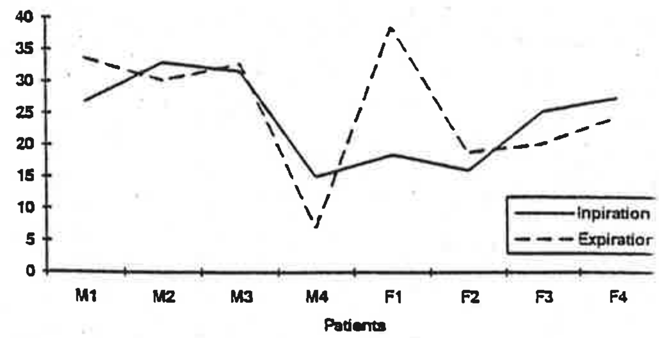


Figure 3

4. Transducer type

In tabel 2 (S/N) obtained with the PCB and B & K transducers are compared for measuring points 3 and 6.

Table 2:

Patient no	S/N (dB) at meas. point 3 for PCB/ B & K transducers			S/N (dB) at meas. point 6 for PCB/B&K transducers		
	supine	1.decub	prone	supine	1.decub	prone
F 1	36/29	34/30	33/26	45/23	42/25	33/20
F 2(fat)	27/29	33/29	38/36	36/33	31/32	33/31
F 3	36/37	40/34	35/38	39/39	38/33	40/41
F 4(skinny)	37/30	34/34	39/35	42/36	31/27	35/38
M 1	40/37	45/43	46/39	44/40	45/40	41/42
M 2	36/39	38/40	37/37	41/40	46/37	44/36
M3(skinny))	38/37	43/38	39/37	43/43	47/45	47/47
M 4(fat)	23/31	37/35	30/31	34/30	36/28	21/27
Mean	34/34	38/35	37/35	41/36	40/33	37/35

Figure 4 shows a typical closing sound and the corresponding energy density spectra (mean of 20 heart cycles) obtained simultaneously with the PCB and B & K transducers in measuring point 3.

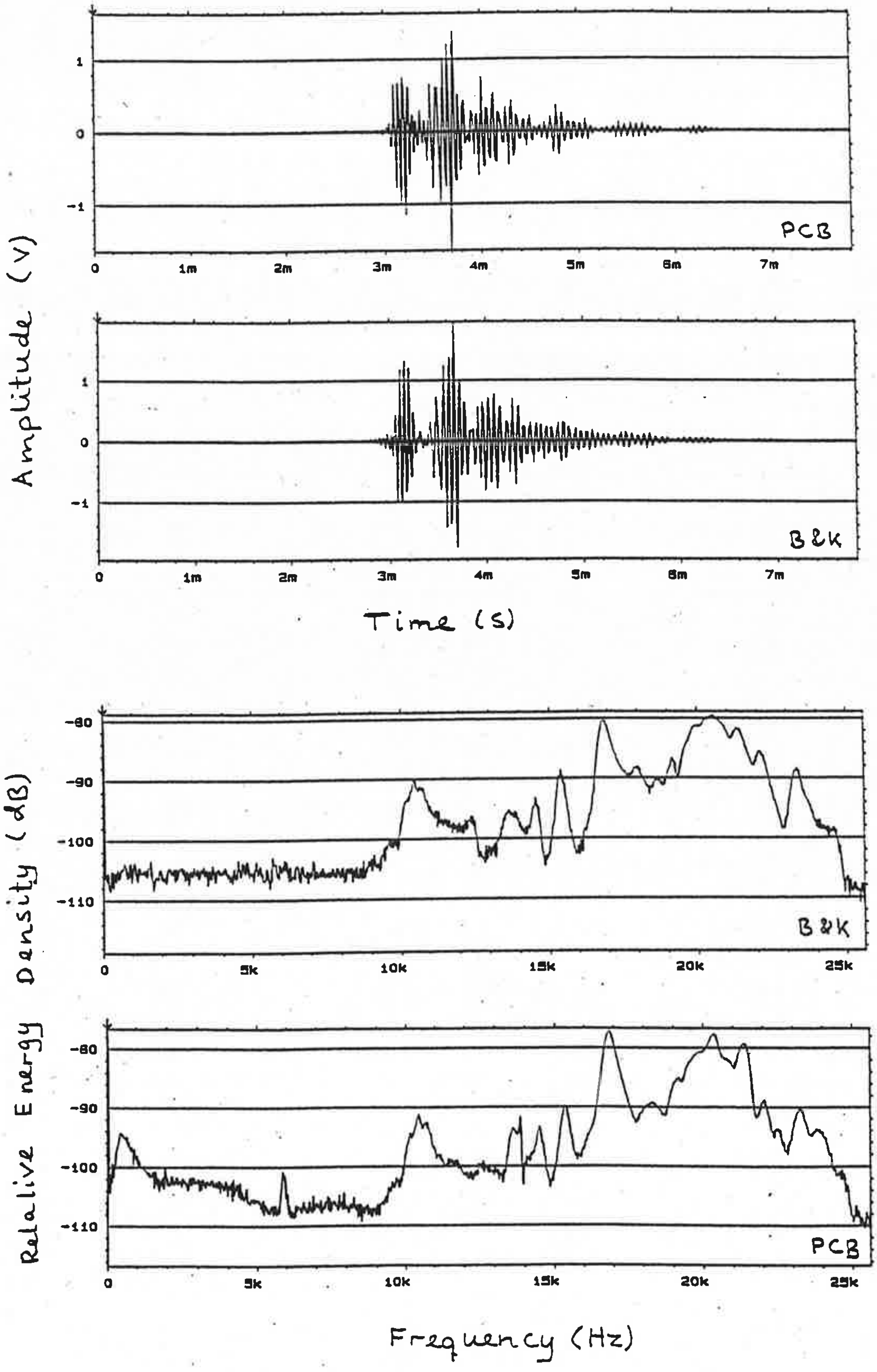


Fig. 4

DISCUSSION / CONCLUSION

This human study of precordial heart sounds from bileaflet mitral valve prostheses has demonstrated the importance of placing the transducer at the optimal position of the chest with the patient in a physical position, which gives the lowest attenuation of heart sounds during transmission from heart to chest surface and with minimum interference from respiration.

1. Precordial measuring site

According to the calculated S/N the best measuring points for both women and men are number 3, 5 and 6 depending on the patients physical position.

2. Physical position

The highest mean S/N was recorded in measuring point 6 with the patients in supine position using the PCB pressure microphone. However, variations of S/N between measuring points are lowest in prone position.

3 Respiratory phase

The ratio of the amplitude of the closing sounds obtained during inspiration and expiration varied from patient to patient in supine position.
In prone position the signals were ~~largely~~ more unaffected by respiration.

4. Transducer type

Depending on measuring point and the patients physical position the S/N obtained with the PCB pressure microphone were typically 2-6 dB better than correspoding values obtained with the B & K accelerometer.

The results from the present study suggest that sounds from mechanical mitral valve prostheses are measured in the precordial area of the distal part of the sternum and fifth left intercostal space.
If only a few heart cycles are needed for the analysis, measurements ~~should~~ could be performed with the patient in supine position during held expiration. If a larger number of heart cycles are required, measurements should be performed in prone position during spontaneous respiration.

FINAL REPORT ON

CLINICAL ASSESSMENT OF PHYSICAL PARAMETERS ON MECHANICAL HEART VALVE SOUNDS

Hans Nygaard[1,2,3], J. Michael Hasenkam [1,2,3], Peter K. Paulsen [2], Jens Leding Kopp[1], Carsten Dollerup Jensen[1]

1. Department of Electronic Engineering, Engineering College of Aarhus.
2. Department of Thoracic and Cardiovascular Surgery, Skejby Sygehus, Aarhus University Hospital.
3. Institute of Experimental Clinical Research, Aarhus University, Denmark.

Corresponding address:
Hans Nygaard, Professor of Biomedical Engineering
Department of Electronic Engineering
Engineering College of Aarhus
Aarhus Teknikum
Dalgas Avenue 2
8000 Århus C
Denmark
Tel. +4586136211 ext. 404
Fax. +458613648

INTRODUCTION

Recent advances in non-invasive and invasive cardiac imaging, along with the development of color Doppler echocardiography have provided the physician with an impressive arsenal of instrumentation for the diagnosis of cardiovascular diseases. However, heart sounds and murmurs remain prime sources of essential information in the discovery and evaluation of diseased heart valves.

It has also been suggested (1-5) that sounds produced by prosthetic heart valves reflect the structural and functional integrity of their components, and that early signs of valve degeneration should be visible in the spectra of the closing or opening sounds.

Stein et al. (6) demonstrated that the dominant frequency of the aortic component of the second heart sound in patients with porcine bioprosthetic valves increased as the duration of insertion increased. Stein et al. (7,8) also found that the characteristic frequency of heart sounds in patients with degenerated porcine bioprosthetic valves becomes abnormally elevated when degeneration is accompained by calcification or fibrosis, which causes the cusps to stiffen.

Mechanical heart valve prostheses, which constitute the majority of the more than 100.000 prosthetic heart valves implanted worldwide each year, generate clicking sounds as a result of the periodic opening and closing movement of the occluder. While the opening click is usually only detectable with phonocardiography, the closing click may well be audible over a considerable distance and may be annoying to the patients as well as to their families.

In theory, any significant alteration in valve properties such as calcification, tissue in-growth, cloth formation, cracking, tearing, or sticking occluding elements should cause changes in the frequency content and intensity of the opening or closing sounds. Therefore spectral analysis of these sounds should provide information concerning valve integrity.

Previous studies have shown that frequency spectra of sounds produced by malfunctioning prosthetic heart valves differ from spectral of properly functioning valves (e.g. 2-4). Donnerstein et al. (5) theorized that sounds created by prosthetic heart valves are influcenced both by cardiac hemodynamics and by intrinsic mechanical and acoustic characteristics of the valve. Certain properties of these sounds might vary with hemodynamic state while other qualities might remain stable and could, therefore,

be used to characterize the valve and possibly detect early valve degeneration.
Considerable research efforts have been devoted in recent years to find diagnostic parameters in heart sound recordings, which could reveal abnormal functioning aspects of implanted prosthetic valves. Certain spectral and temporal parameters have been shown to be potentially useful by e.g. Kien et al. (9), Stein et al. (6-8), Joe et al. (10) Beyar et al. (11) Durand et al. 12 and Baranek et al. (13).
Spectral analysis of the prosthetic valve sounds is particularly attractive because it is noninvasive, atraumatic and potentially very sensitive.
However, detecting abnormal function can be difficult because even a properly functioning mechanical valve may cause turbulent blood flow and have some degree of stenosis and regurgitation, which might change the total spectrum of the recorded sounds.
Moreover, there are all the practical problems regarding the respiratory induced variance of the transthoracic transfer function from the valve to the chest surface, finding the optimal measuring position, separating the important part of the precordial vibration signal in time domain, low frequency resolution caused by small time windows, definition of the optimal spectral feature that can be used to classify valve condition etc.
Köymen et al. (4) studied prosthetic heart valve sounds and suggested that a correct approach to the analysis of heart valve sounds is to assume that a source producing a wide-band sound is exciting a frequency selective system, properties of which are determined by the anatomy and not by the valve. Donnerstein et al. (5) found that the same St. Jude Medical prosthetic valve implanted in different sheeps produced different frequency spectra, supporting the theory of Köymen et al. (4), that factors in addition to the valve itself may influence characteristics of precordial heart sound spectra.
In order to investigate these phenomena properly in humans, it is necessary to pick up the sounds at a point at the chest and during physical and physiological conditions, which gives the best signal - to - noise ratio.

Therefore, the purpose of the present study was to find the maximum signal-to-noise ratio during precordial measurements of sounds from mechanical mitral valve prostheses in humans when changing the following parameters:

1. Precordial measuring site (nine)
2. Physical position of the patient (three)
3. Respiratory phase (two)
4. Transducer type (two)

BACKGROUND

The physical, mechanical, and vibrational aspects of heart sound transmission from the heart and adjacent large vessels have been studied in detail by many researchers using different methods. These studies indicate that the nature of externally recorded heart sounds or vibrations depend upon cardiac action characteristics, site of production of the sound as well as the properties of tissue between the source and the measuring site. The predominant attenuation of the wave-like motion occurs in the most compressible tissues, such as the lungs and adipose tissue.

Wave propagation in an elastic medium can be differentiated as: compressional, shear and surface waves. Human tissue is however, not purely elastic, it has viscous properties as well, which cause dispersion. Dispersion is characterized by causing a frequency dependent propagation velocity, which is negligible in the human tissue for compressional waves in the frequency range of interest for phono- or vibrocardiography (14). Shear and surface waves, on the other hand have a strong dispersion in this frequency range. The propagation velocity of compressional waves in the body is about 1500 m/s. For shear and surface waves the velocities can be calculated to 1.5 m/s for a frequency of 1 Hz to 20 m/s at 200 Hz (15).

There are optimal recording sites for the various heart sounds where the sound intensity is highest because it is transmitted through solid tissues or through a minimum thickness of inflated lung tissue (16). The four basic chest locations where the intensity of sound from the four valves is maximum is shown in figure 1. Faber and colleagues (17,18) studied the transmission of heart sounds to the body surface. They found that vibrations from the valves arrive first and are of maximum intensity, not at the places where one can project the sources (valves) on the surface, but on the classical auscultation areas. Heintzen and Viets (19) studied the transmission of sounds from the chest wall to the heart employing frequencies from 50 to 1000 Hz, and found that the transmission properties was changing during the cardiac cycle.

Meno et al (20) investigated the heart sound propagation in the human thorax using data from a patient with a mechanical aortic valve prosthesis. Two major modes of wave propagation could be clearly distinguised:

1. The longitudinal compressive mode of wave propagation, where the sounds propagated very fast, and
2. transverse shearing or surface wave propagation, where velocities were less than 25 m/s.

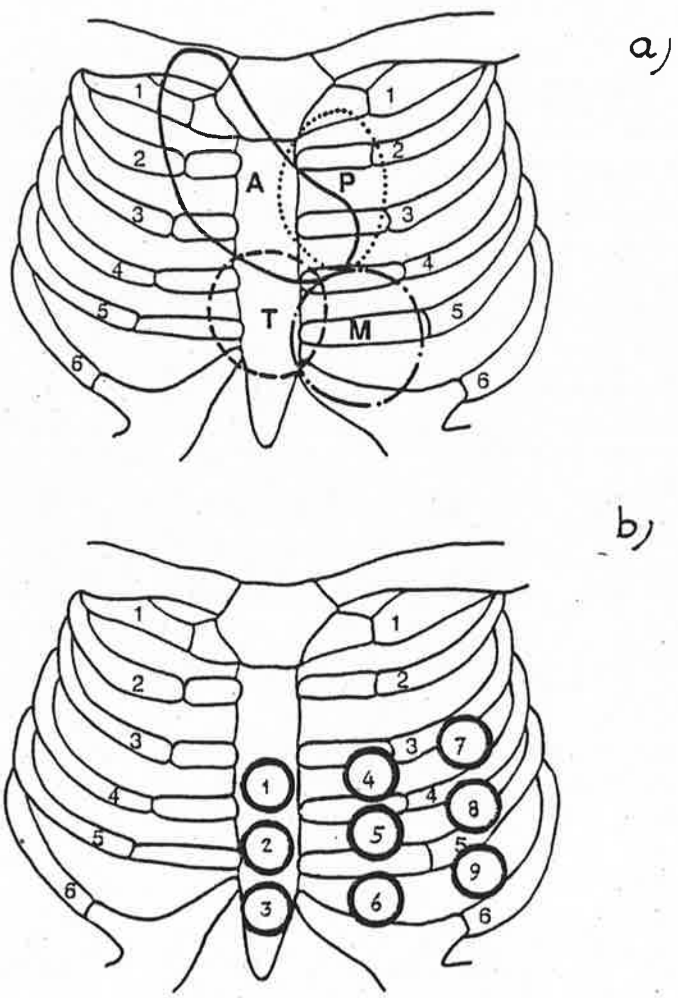


Fig.1 a) The four classical auscultation areas.

b) The nine precordial measuring points used in the present study.

PATIENTS AND METHODS

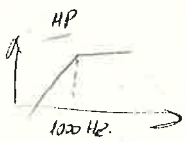
Eight patients, 4 men and 4 women, who underwent mitral valve replacement were investigated. They all had a St. Jude Medical bileaflet prosthesis implanted. After informed consent, interview, classic auscultation, heart rate and blood pressure recording, nine precordial measuring point were defined and marked according to figure 1. Clinical data for the patients are listed in table 1.

Heart sound measurements were performed in a small sound proof/anechoic chamber (3 x 4 m) with the patient in three different physical positions:

1. Supine (Ryg liggende)
2. Left decubitus (Side liggende)
3. Prone (Mave liggende)

In order to perform precordial heart sound measurements with the patient in prone position the examination bed was equipped with a 30 x 30 cm hole and a corresponding shutter.

Heart sound measurements were performed over 10-15 heart cycles during calm spontanious respiration in all 9 precordial measureing point and repeated for the three physical patient positions. Before changing position the same measurement series was made with two different transducer systems:



1. A sound pressure microphone (PCB piezotronics model 106M92) with a built-in preamplifier and a 1000 Hz high -pass filter. The pressure sensitivity was 7250 mV/Bars (72.5 μv/Pa) and the frequency response was flat up to approximately 40 kHz.
   The transducer was supplied by a power unit with adjustable gain (1,10,1000) (PCB, piezotronics, model 480D06).

2. A piezoelectric accelerometer (Brüel & Kjær, type 4371) equipped with a charge amplifier (Brüel & Kjær, type 2635). The charge sensitivity was 1.018 pC/ms^{-2} and the frequency response was flat ($\pm$ 1 dB) up to 20 Khz.

ECG and respiration was measured by a Philips monitor system (type XV1503 and XV1511) and recorded together with the heart sound signals on an instrumentation PCM data recorder (TEAC, type RD-180T). The upper frequency limit (-3dB) for the heart sound channels were 20 KHz.
To secure patient safety the two heart sound systems were equipped with identical isolation units with built-in third order Butterworth 500 Hz high-pass filters.

In addition to the experimental protocol the two measuring systems were compared by placing the two different tranducers closely together at precordial point 3 with the patient in supine position.
The protocol was approved by the Danish Local Ethical Committee, and the patients were informed and gave written and oral consent according to the "Helsinki Declaration II"

Table 1: Patient data

Patient no/sex	Age years	Height cm	Weight kg	BP mmHg	HR min^{-1}	Valve size mm	Diagnosis before MVR and comments
F1	62	172	64	160/95	80	27	MI, Slight dyspnoea
F2	53	160	78	180/90	80	31	MI, MS,CAD, Fat
F3	67	160	56	140/100	120	29	MI, MS, AF
F4	64	158	49	135/80	80	31	MI, skinny
M1	38	176	81	150/90	88	33	MI, active
M2	65	177	77	130/80	88	31	MI, CAD
M3	46	186	72	145/85	80	33	MI, MS, skinny
M4	67	172	94	190/95	88	31	MI, CAD, fat
Mean	58	170	71	154/89	88		

F = Female
M = Male
BP = Blood pressure (systolic/diastolic)
HR = Heart rate
MVR = Mitral valve replacement
MI = Mitral insufficiency
MS = Mitral stenosis
CAD = Coronary artery disease
AF = Atrial fibrillation

Signal analysis was performed off-line using a commerciel signal analyzer (Brüel & Kjær, Dual Channel Signal Analyzer, type 2032). It has a sampling rate of 66 KHz and a 115 dB/octave analog antialiasing filter with 25.6 KHz cut-off frequency. The digital resolution is 12 bit ~ 72 dB.

The signal-to-noise ratio (S/N) was defined as the ratio between the energy of the two closing sounds E_s and the energy of the baseline noise E_n in diastole both calculated within a time window T = 8 ms.

$$(S/N) = 10\log\frac{\frac{1}{T}\int_T v_s^2(t)\,dt}{\frac{1}{T}\int_T v_n^2(t)\,dt} = 10\log\frac{\int_T v_s^2(t)\,dt}{\int_T v_n^2(t)\,dt} = 10\log\frac{E_s}{E_n}\ (dB)$$

where the mean energies were calculated in the frequency domain by estimating the two mean energy density spectra using Fast Fourier Transform (FFT) analysis:

$$(S/N) = 10\log\frac{\int_{fn}^{fø} G_s(f)\,df}{\int_{fn}^{fø} G_n(f)\,df}$$

where G_s (f) and G_n (f) are the mean energy density spectra for closing sounds and the baseline noise respectively. fø = 25,6 KHz was set by the signal analyzer, and f_n = 500 Hz by the high-pass filters.
The diastolic noise energy was only calculated once for each patient position and transducer type.

The following parameters were evaluated:

1. Measuring site: 1-9
2. Patient position: supine, left decubitus or prone.
3. Respiratory phase: inspiration or expiration
4. Transducer type: B & K accelerometer or PBC pressure microphone.

RESULTS

1. Measuring site

S/N was calculated in all nine measuring points for the two transducer systems. In table 2 S/N for the best and second best measuring points are shown for all patients.

Table 2:

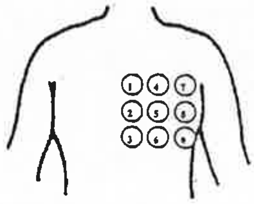
Patient no	Best/ second best, measuring points for PCB transducer			Best/second best measuring points for,B & K transducer		
	supine	decub.	prone	supine	decub.	prone
F 1	6/8	6/5	9/8	3/9	7/3	5/8
F 2 (fat)	6/8	1/3	3/5	3/6	2/1	5/3
F 3	6/5	3/9	5/9	6/1	3/6	5/6
F4(skinny)	6/5	5/3	4/9	6/9	3/5	6/9
M 1	6/5	4/6	5/3	1/6	2/1	1/2
M 2	6/9	6/2	6/2	6/3	3/2	2/3
M3(skinny)	6/5	6/3	5/4	6/3	6/5	5/6
M 4(fat)	6/5	5/3	2/5	3/6	2/3	2/1
"Mean"	6/5	6/3	5/9	6/3	3/2	5/6

{ ?

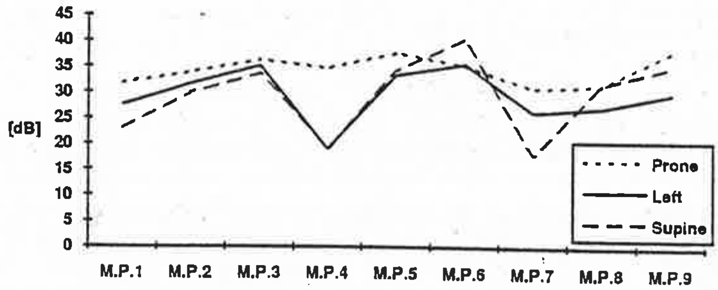
2. Patient position

Plots of the mean S/N for the four women and four men measured with the PCB and B & K transducers are shown for all nine measuring points in figure 2.

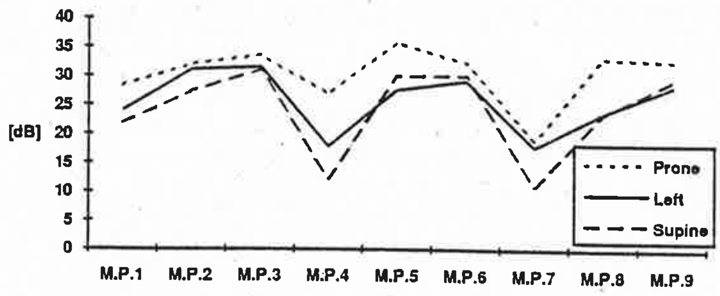
The three physical patient positions are plotted seperately.



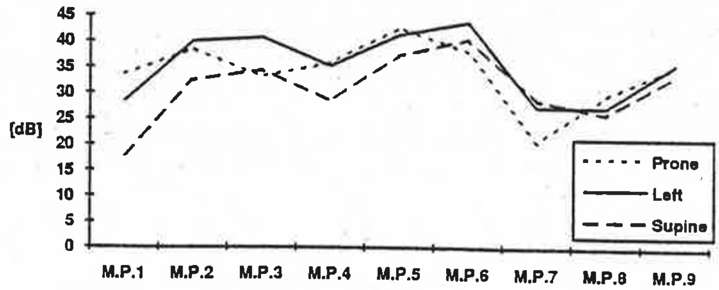
Women: PCB



Women: B&K



Men: PCB



Men: B&K

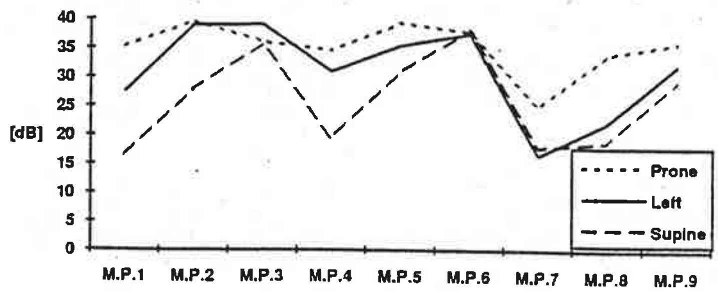
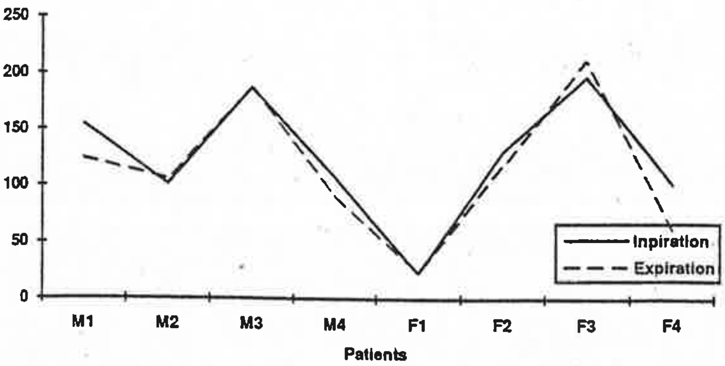


Fig. 2

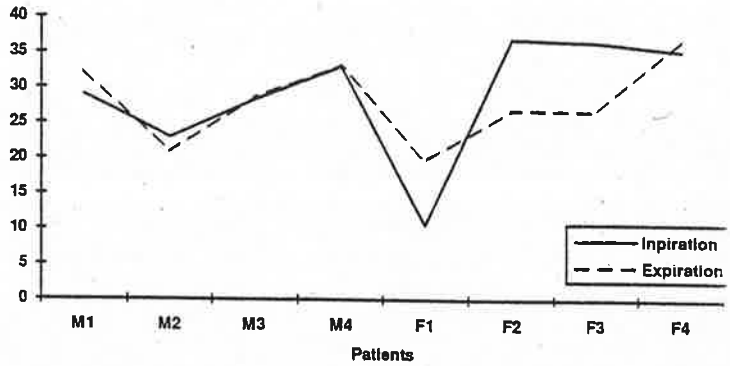
3. Respiratory phase

Peak-peak values of recorded closing sounds in measuring point 3 in respiratory inspiration and expiration phase are shown in figure 3 for all nine patients in supine and prone position measured with both transducer systems.

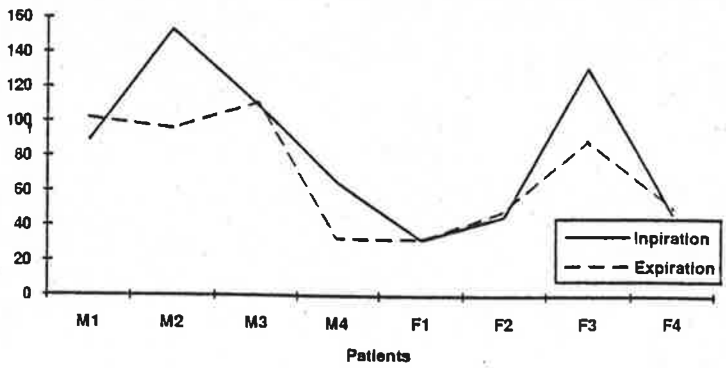
Prone position in M.P. 3 for women and men displayed in inpiration and expiration phase with B&K-transducer



Prone position in M.P.3 for women and men displayed in inpiration and expiration phase with PCB-transducer



Supine position in M.P.3 for women and men displayed in inpiration and expiration phase with B&K- transducer



Supine position in M.P.3 for women and men displayed in inpiration and expiration phase with PCB-transducer

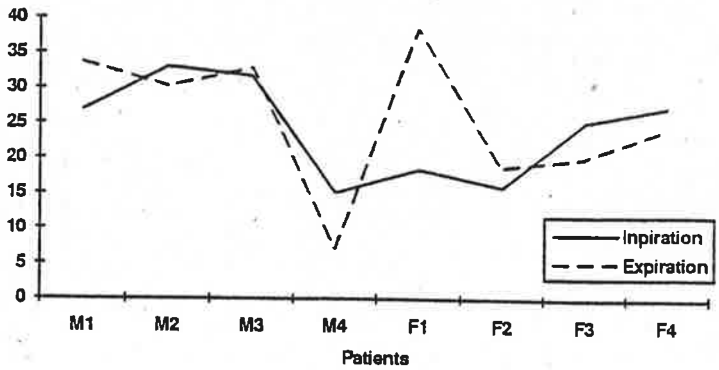


Figure 3

4. Transducer type

In table 3 (S/N) obtained with the PCB and B & K transducers are compared for measuring points 3 and 6.

Table 3:

Patient no	S/N (dB) at meas. point 3 for PCB/ B & K transducers			S/N (dB) at meas. point 6 for PCB/B&K transducers		
	supine	1.decub	prone	supine	1.decub	prone
F 1	36/29	34/30	33/26	45/23	42/25	33/20
F 2(fat)	27/29	33/29	38/36	36/33	31/32	33/31
F 3	36/37	40/34	35/38	39/39	38/33	40/41
F 4(skinny)	37/30	34/34	39/35	42/36	31/27	35/38
M 1	40/37	45/43	46/39	44/40	45/40	41/42
M 2	36/39	38/40	37/37	41/40	46/37	44/36
M3(skinny)	38/37	43/38	39/37	43/43	47/45	47/47
M 4(fat)	23/31	37/35	30/31	34/30	36/28	21/27
Mean	34/34	38/35	37/35	41/36	40/33	37/35

Figure 4 shows a typical closing sound and the corresponding energy density spectra (mean of 20 heart cycles) obtained simultaneously with the PCB and B & K transducers in measuring point 3.

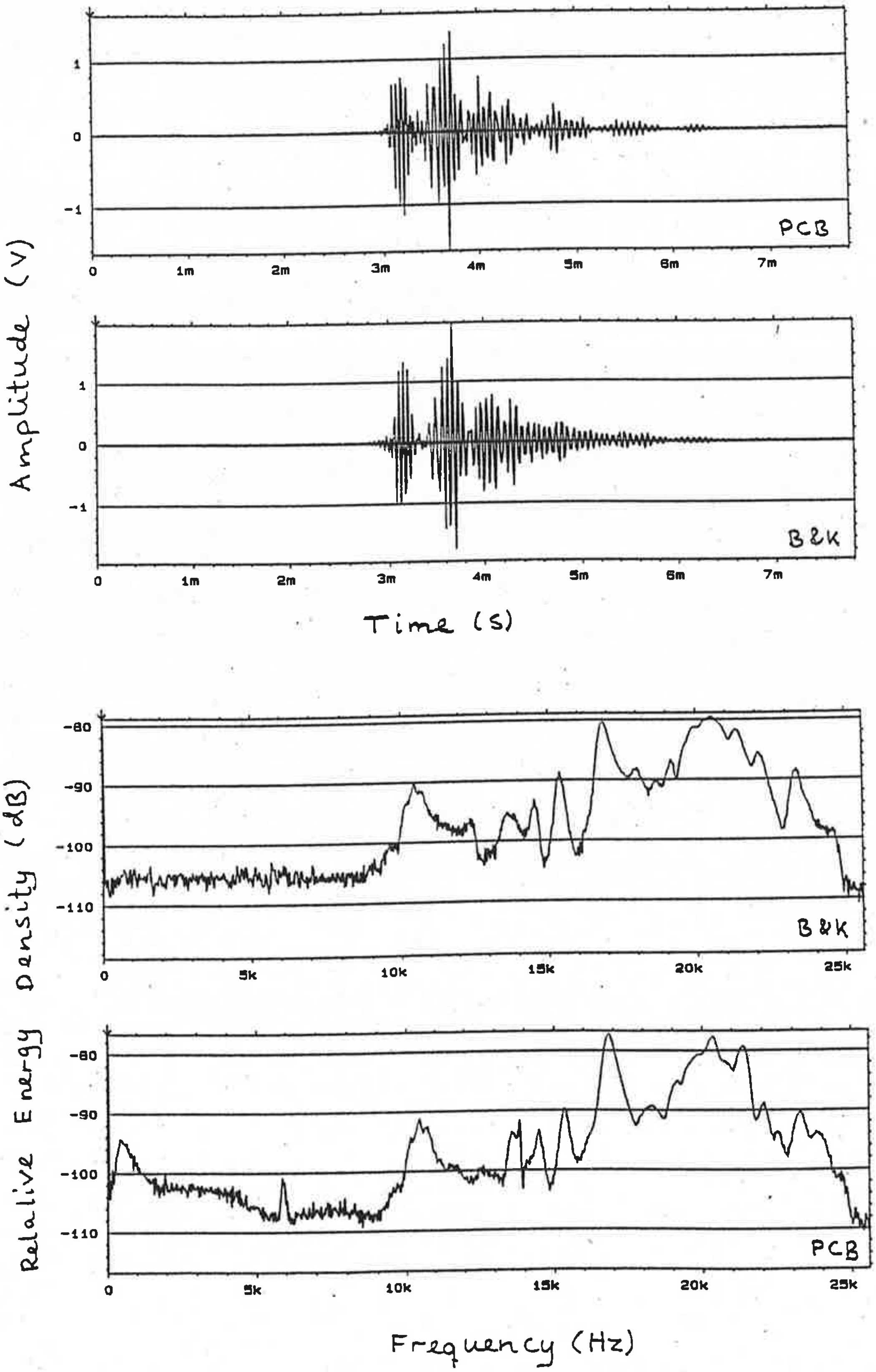


Fig. 4

DISCUSSION / CONCLUSION

This human study of precordial heart sounds from bileaflet mitral valve prostheses has demonstrated the importance of placing the transducer at the optimal position of the chest with the patient in a physical position, which gives the lowest attenuation of heart sounds during transmission from the heart to the chest surface, and with minimum interference from respiration.

1. Precordial measuring site

According to the calculated S/N the best measuring points for both women and men are number 3, 5 and 6 depending on the patients physical position.

2. Physical position

The highest mean S/N was recorded in measuring point 6 with the patients in supine position using the PCB pressure microphone. However, variations of S/N between measuring points are lowest in prone position.

3 Respiratory phase

The ratio of the amplitude of the closing sounds obtained during inspiration and expiration varied from patient to patient in supine position.
In prone position the signals were largely unaffected by respiration.

4. Transducer type

Depending on measuring point and the patients physical position the S/N obtained with the PCB pressure microphone were typically 2-6 dB better than correspoding values obtained with the B & K accelerometer.

The results from the present study suggest that sounds from mechanical mitral valve prostheses are measured in the precordial area of the distal part of the sternum and fifth left intercostal space.
If only a few heart cycles are needed for the analysis, measurements should be performed with the patient in supine position during held expiration. If a larger number of heart cycles are required, measurements should be performed in prone position during spontaneous respiration.

REFERENCES

1. Stein PD, Sabbah HN, Lakier JB, Kemp SR, Magilligan DJ Jr. Fundamental basis and clinical validation of frequency analysis of the valve closure as an indication of stiffening of bioprosthetic valves. J Cardiography 1984;14:57-58.

2. Suobank DW, Yoganathan AP, Harrison EC, Corcoran WH. A quantitative method for the in vitro study of sounds produced by prosthetic aortic heart valves. Part I: analytical consideratoins. Med & Biol Eng & Comput 1984;22:32-39.

3. Kagawa Y, Sato N, Nitta S. Real-time sound spectroanalysis for diagnosis of malfunctioning prosthetic valves. J Thorac Cardiovasc Surg 1980;79:671-679.

4. Koymen H, Altay BK, Ider YZ. A study of prosthetic heart valve sounds. IEEE Trans Biomed Eng 1987; BME-34:853-863.

5. Donnerstein RL, Scott WA, Vasu A, Copeland JG. Acoustic analysis of the closing sounds of bileaflet prosthetic valves in a sheep model. J Thorac Cardiovasc Surg 1991;101:1060-1068.

6. Stein PD, Sabbah HN, Lakier JB, Goldstein S. Frequency spectrum of the aortic component of the second heart sound in patients with normal valves, aortic stenosis and aortic porcine xenografts. Am J Cardiol 1980;46:48-52.

7. Stein PD, Sabbah HN, Lakier JB, Magilligan DJ Jr, Goldstein S. Frequency of the first heart sound in the assessment of stiffening of mitral bioprosthetic valves. Circ 1981;63:200-204.

8. Stein PD, Sabbah HN, Lakier JB, Kemp SR, Magilligan DJ Jr. Frequency spectra of the first heart sound and or the aortic component of the second heart sound in patients with degenerated porcine bioprosthetic valves. Am J Cardiol 1984;53:557-561.

9. Kien GA, Jeffries B, Katz HV, Herman BA, Carey RF, Chwirut DJ, Bushar HF. Digital acoustical analysis of normal and bimodal Bjork-Shiley 60^0 convexo-concave heart valves. Am J Cardiol 1990;66:849-854.

10. Joo TH, McClellan JH, Foale RA, Myers GS, Lees RS. Pole-zero modeling and classification of phonocardiograms. IEEE Trans 1983; BME-30:110-118.

11. Beyar R, Levkovitz S, Braun S, Palti Y. Heart sound processing by average and variance calculation- Physiologic basis and clinical implications. IEEE Trans Biomed Eng 1984;BME-31:591-596.

12. Durand LG, Blanchard M, Sabbah HN, Hamid MS, Kemp SR, Stein PD. A Bayes model for automatic detection and quantification of bioprosthetic valve degeneration. Math Comput Modelling 1988;11:158-163.

13.. Baranek HL, Lee HC, Cloutier G, Durand L-G. Automatic detection of sounds and murmurs in patients with Ionescu-Shiley aortic bioprostheses. Med & Biol Eng & Comput 1989;27:449-455.

14. Verburg J. Transmission of vibrations of the heart to the chestwall. Adv cardiovasc Phys 1983;5:84-103.

15. Verburg J, van Vollenhoven E. Phonocardiography: physical aspects and clinical uses. In: Non invasive physiological measurements. Rolfe P. (Ed). Academic Press, London, 1979:213-259.

16. Feruglio GA. An intracardiac sound generator for the study of the transmission of heart murmurs in man. Am Heart J 1962:63:232-238.

17. Faber JJ, Burton AC. Spread of heart sounds over chest wall. Circ Res 1962;11:96-107.

18. Faber JJ. Dampning of sound on the chest surface. Circ Res. 1963;13:352-358.

19. Heintzen P, Vietor KW. The diacardiac phonogram. Am Heart J 1963;65:59-67.

20. Meno F, Reddy PS, Bernardi L. Heart sound propagation in the human thorax. Clin Phys Physiol Meas 1985; 123-129.