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In Vitro Sound Spectral Analysis of Prosthetic Heart Valves by Mock Circulatory System

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A comparative study was made of the sounds produced by normal prosthetic valves(St. Jude Medical, Bjork-Shiley, polymer) with those produced by the same valves but having simulated thrombosis at the stent, hinge, or strut. Comparisons of the closing sound were made for the power frequency spectra associated with individual valves. We used periodogram approach to obtain the spectral characteristics of the valve prostheses. The closing sound of the abnormal mechanical valves displayed lower apparent peak frequency. But the abnormal polymer valve produced higer apparent peak frequency. The results showed that frequency spectra gave information pertinent to the simulated malfunction. Sound spectral analysis is believed to be a simple and a good diagnostic tool for detection of prosthetic valve malfunction. Also it seemed to be superior to other methods such as phonocardiography and echocardiography.

Key Words: Fast Fourier transform, spectral analysis, mock circulatory system

The malfunction of prosthetic heart valves is a serious problem for the patients who received prosthetic valve replacement. Early and late complications including thromboemboli, hemolysis, sepsis, leaks, dehiscence, and stenosis have been noted after operation. A number of patients who receive prosthetic valves are still subjected to replacement of the implanted valves or thrombolytic theraphy because of thrombus formation. Thrombus formations on the mechanical heart valves is a major cause of morbidity and mortality after valve replacement(Kirklin and Barratt-Boyes, 1993). Thrombus formations on the valve often interfere with its function by causing occluder immobility, which in turn results in desastrous hemodynamic deterioration. Consequently, careful and frequent follow-up with regard to prosthetic function is important since serious complications may occur with little or no clinical warning. Several diagnostic methods are available for detection of malfunctioning prosthetic valves. Existing techniques can be separated into invasive techniques and noninvasive techniques. The noninvasive methods can be further divided into active methods, which transmit and receive a signal, and passive methods, which merely listen to signals generated by the heart. Noninvasive methods are preferred to invasive methods because they are safer and more convenient and lend themselves to long term patient studies.

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The sound spectral analysis of prosthetic heart valves is a more sensitive and safer technique in evaluating valvular performance than the echocardigraphy. Since early detection of valve thrombosis is imperatives, sound spectral analysis of prosthetic heart valve have been studied extensively. The development of digital computers and algorithms such as the fast Fourier transform (FFT) allowed rapid calculation of discrete power-density spectra with well defined resolution of frequencies. Previous studies by Stein *et al.* (1984), Foale *et al.* (1983), and Joo *et al.* (1983) emphasized the diagnostic potential of spectral analysis of bioprosthetic valve closure sounds for the detection of valvular degeneration. These studies showed that the apparent frequency of porcine valve closure sounds shifts toward higher frequencies following valve leaflet calcification and stiffening. Recently, Sato *et al.* (1993) analyzed specific patterns of thrombus formation in Bjork-Shiley tilting standard disc prostheses in relation to the sound spectral analysis of their click sounds. They demonstrated that the sound spectral analysis is an extremely useful diagnostic tool for early detection of thrombosis in the Bjork-Shiley tilting standard disc prostheses.

This work reported the sound characteristics of mechanical valves and a polymer valve for the normal and abnormal condition in vitro. It is determined by comparative analysis whether the sound data contained sufficient, useful information for diagnostic purposes. The thrombosed valve condition was simulated by applying silicon rubber gel at each valve prosthesis. For the in vitro study, a mock circulatory system was designed to replicate the physiological pulsatile flow in the human circulatory system.

MATERIALS AND METHODS

Two mechancial valves, a Bjork-Shiley convexo-concave disc valve(BS) and a St. Jude Medical valve(SJM) were used to measure valve sound for the normal and abnormal condition. A valve sound from a monoleaflet polymer valve(PV) also was measured to compare its sound charateristics with those of mechancial valves. PV was developed in our laboratory in order to be used for ventricular assist device(Kim *et al.* 1993b). It is made from polyurethane with the outside frame diameter being 22 mm. The tissue annulus diameter (sewing ring diameter) of the mechanical valves is 27 mm. The abnormal valve condition of thrombus attachment was simulated by applying silicone rubber gel at each prosthetic valve because the mechanical property of silicon rubber gel is similar to that of the early stage of thrombus. The silicon rubber gel was applyed at minor and major strut of BS, at the hinge of SJM, or at the frame of PV where the sites are most susceptible and probably the original location of thrombus for-

(a) Bjork-Shiley (b) St. Jude Medical (c) polymer valve

Fig. 1. *Photograph showing mechanical valves and a polymer valve, which have simulated thrombosis.*

mation(Sato *et al.* 1993). This attachment reduced the disc motion by 0.3~0.5 mm relative to the fully close position. The simulated thrombosed valves are shown Fig. 1. Elements of the mock circulatory system are shown schematically in Fig. 2. The flow system consists of the diaphragm pump, a flexible atrium, a compliance box, resistance clamp, rotameter, and resorvoir. The fluid in a closed-loop is driven by a diaphragm pump connected to pneumatic driver. Further details of the mock circulatory system are explained in Kim *et al.*(1993a).

The prosthetic valve was mounted in the aortic position in the mock circulatory system. Simultaneous measurements were made of sound, ventricular pressure, aortic pressure, and volumetric flow. A microphone transducer

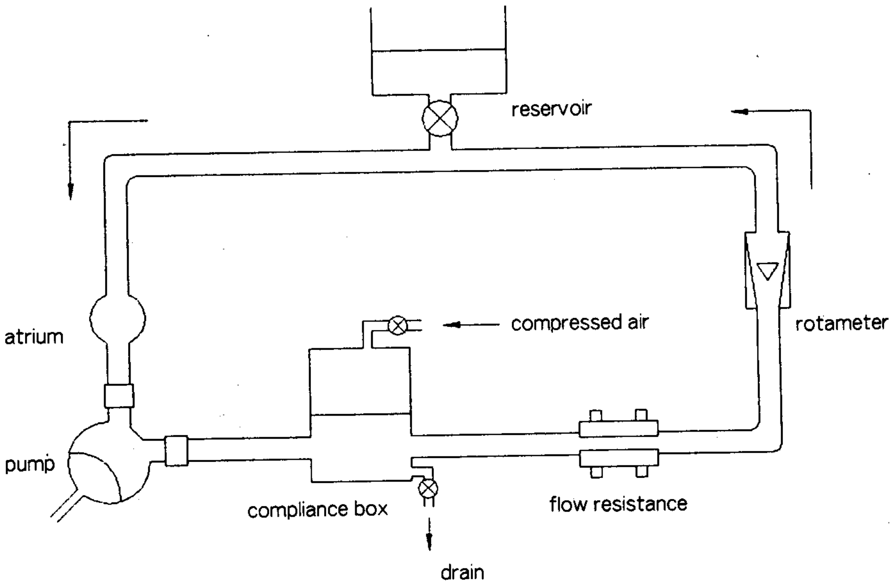

Fig. 2. *Schematic view of the mock circulatory system.*

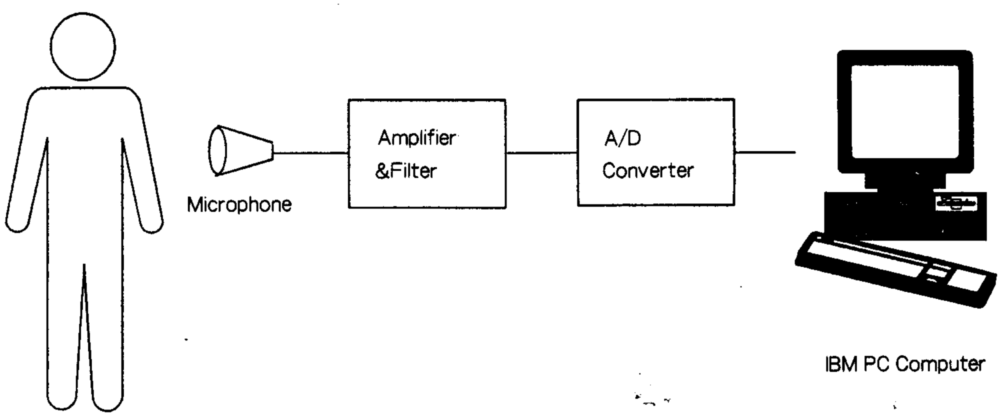

Fig. 3. *Recording precedure of sound spectral analysis.*

(pulse transducer, Electronics for Medicine, USA) was placed within the aortic flow section to measure the sound. The sound signals were amplified, filtered on an multi-channel photographic recorder(VR-6, Electronics for Medicine, USA). The signal was filtered below 50 Hz and above 500 Hz, and then processed through a 12 bit data translation analog-to digital converter board (DT2801-A, Data Translation, USA) contained in an IBM-PC/386 personal computer. Recordings were made during 10 seconds at a sampling rate of 1kHz. Each data was stored on hard disk of the computer. Fig. 3 schematically describes the recording procedure of the system. In this study, we used periodogram approach to obtain the spectral characteristics of the valve prostheses. Welch(1967) has introduced a modification of the periodogram which is particularly well adaped to the FFT algorithm and reduces both the variance and the bias of the periodogram. The signal x(t) is first sampled and divided into R segments of duration N and the spectrum $S_{XX}(w)$ is estimated with

$$S_{XX}(W)=\frac{1}{RNU}\sum_{r=1}^{R} | X_r(e^{jw}) |^2$$

where

$$X_r(e^{jw})=\sum_{n=0}^{N-1} X_r(n)w(n)e^{-jwn}$$

and U is the power of the windowing function.

RESULTS

The sounds were measured at a systolic du-

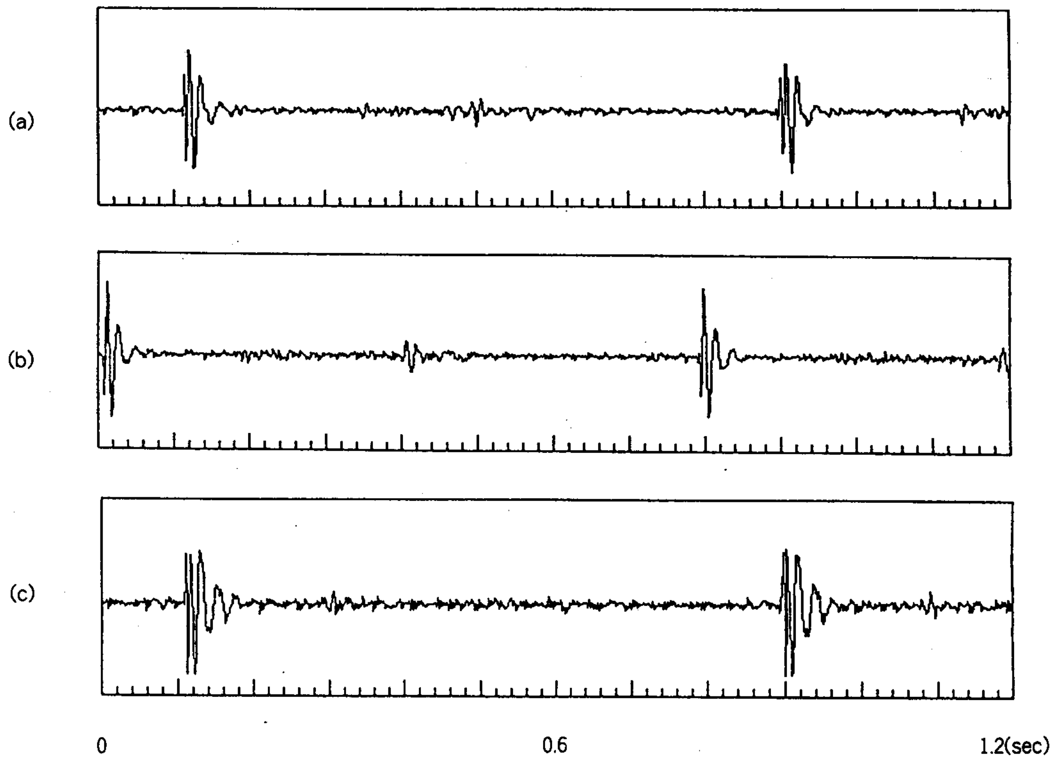

Fig. 4. *Phonocardiograhic display of the normal valve.*
(a) St. Jude Medical (b) Bjork-Shiley (c) polymer

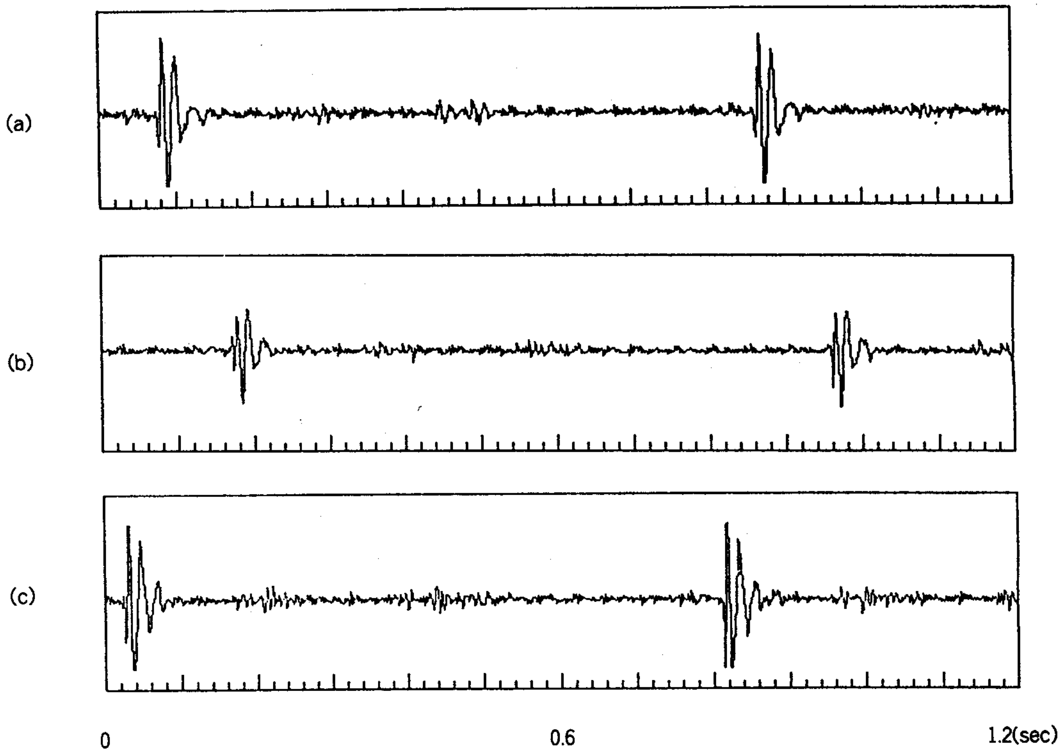

Fig. 5. Phoncardicgraphic display of the abnormal valve.
(a) St. Jude Medical (b) Bjork-Shiley (c) polymer

ration of 45% and a heart rate of 70 bpm. The left atrial pressure was maintained at 15 mmHg and the cardiac output of the pump was set at 5 L/min. The sounds vary significantly depending upon many factors including transducer location, impedance matching of the transducer/conduit interface and the position of the pump. Fig. 4 and 5 show phonocardiographic display of each normal and simulated thrombosed valve prostheses. Technically satisfactory phonocardiographys were obtained from normal and abnormal valves. The estimated duration of each closing component is 64 msec, which gives 64 data samples. In order to obtain a good spectral estimate it is important to select an appropriate closing sound component from the entire phonocardiography. In this study a closing sound component of the shape which occurred most frequently during recording was selected. The average difference between two components selected at random in terms of the apparent peak frequency was less than 10%. A selected component of 64 data points was padded with zeros and a 1028-point FFT computed. The logarithm of the amplitude of each transform coefficient was taken to convert to decibels(db). Fig. 6 to 8 show the frequency spectra obtained for each prosthetic heart valve. Each frequency spectrum contains two or more frequency peaks. The apparent peak frequency produced by the normal SJM and normal BS is higher than that of the each simulated thrombosed one. The apparent peak frequency of the abnormal SJM is lower by 21 % than that of the normal one. For the abnormal BS it is lower by 16% than that of the normal one. Both normal mechanical valves shows similar frequency spectra with each other but abnormal valves shows differ-

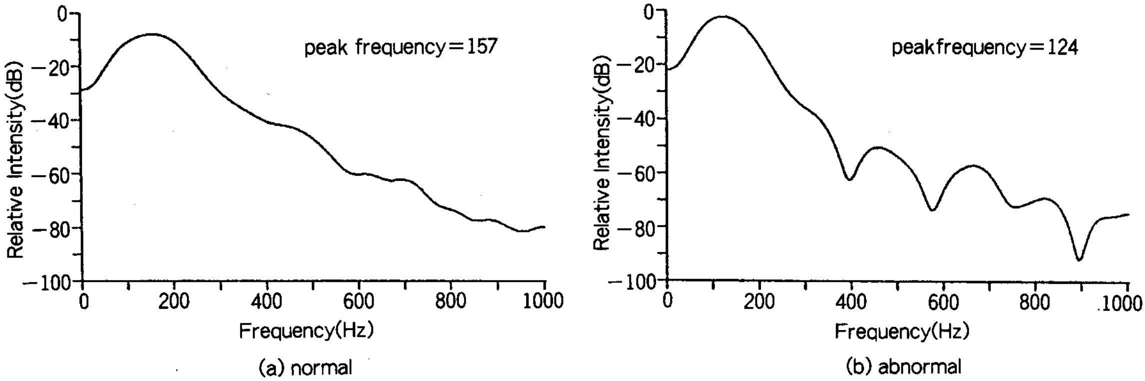

Fig. 6. *Frequency spectra of St. Jude Medical valve.*

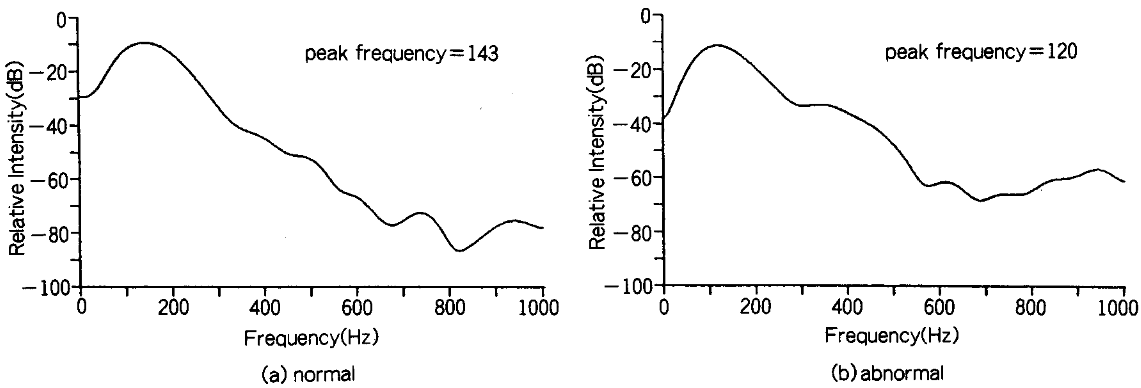

Fig. 7. *Frequency spectra of Bjork-Shiley valve.*

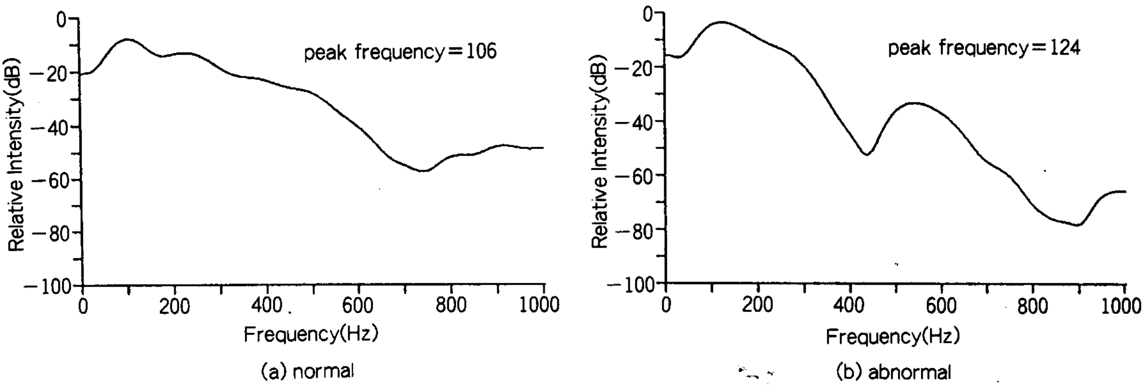

Fig. 8. *Frequency spectra of polymer valve.*

ent frequency spectra. Frequency spectra produced by abnormal SJM contains several peaks. In contrast to the mechanical valves, the apparent peak frequency produced by abnormal PV is higher by 17% than that of the normal one. Frequency spectra produced by abnormal PV contains more frequency peaks than that of normal one.

DISCUSSION

We have shown that spectral analysis of valvular sound could facilitate the diagnosis of mechanical valve dysfunction caused by thrombosis. Simulated thrombosis affects the closing sound of the valve which results in a decrease or an increase of the frequency of vibration of the valve. The adhesion of thrombus to the prosthetic valves may interfere with high-frequency components because of their buffering effect or may decrease the natural frequency of the material of the prosthetic valve. For the mechanical valves simulated thrombosis decrease the apparent peak frequency of the closed valve but for the polymer valve its apparent peak frequency increases. A localized thrombosis at the hinge area of SJM causes progressive restriction of the disc motion, which may immobilize the disc in a semiclose position. When a thrombus involves the major and minor strut of BS as simulated in this study, it easily impedes full closing of the disc. The central portion of the minor strut is the most susceptible location of thrombus formation for BS. These changes the closing click of mechanical valves and also decrease the peak frequency of sound spectra. For the thrombosed PV the peak freuency of spectra increased because the simulated thrombosis is more rigid than the material of the stent and leaflet. Apparent peak frequency difference between normal and abnormal PV was not significant compared to that of the mechanical valves. It indicates that frequency spectra highly depends upon the material of the colliding disc and stent. The strut and stent of mechanical valves are composed of hard materials which produce higher-frequency components than the valvular sounds of the PV. The estimated frequency spectra suggest that a simple signal processing algorithm may be useful in the diagnosis of prosthetic valve dysfunction.

In this study a conventional FFT-based method was used to estimate the frequency spectrum of the prosthetic valve sound. A high resolution modern parametric method based on all-pole and pole-zero modeling can be used to completely characterize the spectrum of the prosthetic valves(Durand *et al.* 1986). These positive results would lead to further in vitro studies to provide a preliminary databank and then to equivalent or related in vivo studies. A large patient population will be needed to prove the effectivenes of this system. The classification of prosthetic valves into normal or abnormal by spectrum analysis of the phonocardiography based on pattern recognition should be considered. We believe that this system could become very useful diagnostic tool for early detection of thrombosis in the mechanical valves.

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