Clinical Studies

A Mass-Spring Model Hypothesis of the Genesis of the Physiological Third Heart Sound

Carlo Longhini, M.D., Silvio Aggio, M.D., Enrico Baracca, M.D., Donato Mele, M.D., Carmelo Fersini, M.D., and André E. Aubert, Ph.D.*

SUMMARY

A study on the genesis of the third heart sound (S3) based on the mass-spring model is presented. In such a system the natural frequency of vibration depends on the stiffness constant and the mass according to a physical law. The amplitude versus frequency spectra of S3 of 19 patients were obtained using the FFT algorithm together with mono- and two-dimensional echocardiographic parameters. Each echo parameter was correlated with the relative energy contained in each of the 15 Hz bands in which the normalized average spectrum of S3 of each subject was divided. The relative energy of each band was related to echocardiographic parameters. Significant correlation coefficients were found between the diameter of the left ventricle measured at the end of the rapid filling phase, the thickness of the posterior wall and of the interventricular septum at this moment, and the energy contained in certain frequency bands. The statistical correlations we have revealed are consistent with the model postulated in our hypothesis.

Additional Indexing Words:
Third heart sound Spectral analysis Echocardiography Phonocardiography

The third heart sound (S3) is composed of a group of low frequency vibrations occurring in early diastole, easily audible and recordable at the point of maximal apical impulse in a high percentage of normal children and adolescents.1),2)

The physiological mechanisms underlying the genesis of this phenomenon are still somewhat unclear. Three principal theories have been proposed:

1) The valvular theory attributes S3 to the sudden stretching of the val-
vular apparatus due to the inward rush of blood during the rapid filling phase of the cardiac cycle. 2) The impact theory maintains that S3 is due to the striking of the heart against the thoracic wall. 3) The theory of left ventricular distension states that S3 is produced at the end of the rapid filling phase when the elastic limits of the left ventricle are reached.

We have studied the problem of the genesis of S3 according to the physical law of a vibrating mass-spring system. In such a system the natural vibration frequency \( F(n) \) is related to the mass \( m \) and the stiffness factor \( k \) according to a widely known equation: \( F(n) = \frac{1}{2\pi} \sqrt{k/m} \). In order to identify the heart structures corresponding to the "\( k \)" and "\( m \)" parameters, we have employed spectral analysis and echocardiographic techniques in search of the coefficients relating spectral frequency to cardiac structures.

**Materials and Methods**

a) Subjects

Nineteen normal subjects, mean age 21±7 years, who had S3 present on the phonocardiogram, were studied. All subjects were free of history or physical findings suggestive of cardiovascular disease, and the electrocardiogram (ECG), X-ray, mono- and two-dimensional echocardiograms were within normal limits.

b) Spectral analysis

A phonocardiogram (PCG) was taken at the apex during held expiration. A lead II ECG was simultaneously recorded. A contact-type pre-amplified piezoelectric microphone (OTE Biomedica, model 99140092130) was used. It was calibrated on a vibrator showing a flat response curve from 7 to 1000 Hz. The signal was passed through a T-type Maass & Weber filter, with a cut-off above 650 Hz, and connected to an OTE EP12 polygraph.

The ECG and PCG were digitized using an 8-bit A/D converter controlled by a 6510/c microprocessor with a 1282 Hz sampling frequency, yielding a Nyquist frequency of 641 Hz.

The signals were processed to demean in order to abolish the continuous component. The S3 was extracted with an interactive program using a Hanning window of 100 msec operated on the data file. The Hanning window was surrounded with 0-padding data, building up a data record of 512 points (400 msec). This record was analyzed employing the Fast Fourier Transform obtaining frequency versus amplitude spectra ranging from 0 to 500 Hz at 2.5 Hz intervals.
For each subject the average of eight spectra was obtained. The spectra of all patients were normalized with respect to peak amplitude and then divided into 15 Hz bands (Fig. 1). For each of these bands the area under the curve of the spectrum was calculated using a trapezoidal technique and assumed as an index of the energy contained in the band. This area was then normalized with respect to the total area of the curve of the entire spectrum.\textsuperscript{15}

c) Echocardiographic parameters

The echocardiographic mono- and two-dimensional studies were performed using a commercially available sector scanner. Patients were examined during held expiration and the heart was visualized using parasternal and apical transducer locations. The M-mode tracings were recorded together with a phonocardiogram derived from the apex.

The following parameters were considered: a) left atrial volume, employing the monoplane ellipsoid formula\textsuperscript{16} using the transverse and longitudinal left atrial diameters from parasternal and apical four-chamber views;
b) left atrial emptying index calculated by the method of Strunk et al.\textsuperscript{17}; c) mitral valve area, measured in the parasternal short axis view\textsuperscript{18}; d) left ventricular diastolic diameter measured at the moment of S3\textsuperscript{18}; e) interventricular septum and left ventricular posterior wall thickness, measured at the same moment\textsuperscript{18}; f) maximum diastolic slope of the septum and posterior left ventricular wall\textsuperscript{18}; g) left ventricular ejection fraction\textsuperscript{18}; h) left ventricular mass\textsuperscript{18}; i) fractional shortening of the left ventricle.\textsuperscript{18}.

The echocardiographic parameters were correlated with relative energy in the frequency bands.\textsuperscript{19,20}

d) Statistics

Statistical analysis was accomplished using linear regression analysis and standard programs. The echocardiographic parameters were correlated among themselves and with the relative energy in each frequency band. Statistical significance was accepted at the probability level of $p < 0.05$. 
RESULTS

a) Spectrum of S3

The mean amplitude versus frequency spectrum of S3 is displayed in Fig. 1. It appears as a monophasic curve with 75.05% of total energy contained in the frequency range from 0 to 60 Hz and with a 27.66±7.6 Hz frequency peak.

b) Echo-phonocardiographic correlations

Significant correlation coefficients were found between the diameter of the left ventricle measured at the end of rapid filling (DS3; Fig. 2), the thickness of the posterior wall (PWTS3; Fig. 3) and of the interventricular septum (ISTS3; Fig. 4) at this moment, and the energy contained in certain frequency bands, as is shown in Table I.

DISCUSSION

The data obtained show a good positive correlation between the energy
Fig. 4. The thickness of the interventricular septum at the moment of S3 (ISTS3) in mm on the horizontal axis is displayed versus the energy content in a) 0–15 Hz, b) 15–30 Hz, c) 30–45 Hz, d) 45–60 Hz frequency bands on the vertical axis.

Table I. Correlation Coefficients between Energy Bands and Echocardiographic Parameters

<table>
<thead>
<tr>
<th>Frequency Bands</th>
<th>0–15 Hz</th>
<th>15–30 Hz</th>
<th>30–45 Hz</th>
<th>45–60 Hz</th>
<th>60–75 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS3</td>
<td>0.791***</td>
<td>0.749***</td>
<td>-0.591**</td>
<td>-0.822***</td>
<td>-0.669**</td>
</tr>
<tr>
<td>ISTS3</td>
<td>-0.792***</td>
<td>-0.680**</td>
<td>0.269</td>
<td>0.544*</td>
<td>0.592**</td>
</tr>
<tr>
<td>PWTS3</td>
<td>-0.802***</td>
<td>-0.697***</td>
<td>0.454</td>
<td>0.681**</td>
<td>0.562*</td>
</tr>
</tbody>
</table>

* p<0.05, ** p<0.01, *** p<0.001.

contained in the 0–15 and 15–30 Hz bands and the diameter of the left ventricle at the moment of S3 (DS3). The negative correlation coefficient between the energy of these bands and the thickness of the posterior wall (PWTS3) and the interventricular septum (ISTS3) were also statistically significant.

Considering the above mentioned structures as elements of a vibrating system, we have postulated the vibration constituting S3 as being generated according to the physical relationship already mentioned. We have as-
sumed the diameter of the left ventricle as an estimation of the vibrating mass (m). Since the mass can be expressed as the product of volume and density and considering blood density as constant, the volume contained in the left ventricle can be computed from Teichholz's formula. PWTS3 and ISTS3 have been chosen as an estimation of the rigidity of the system (k). In fact, as demonstrated by Gaasch et al22) and by Mirsky,23) the stiffness of the ventricular chamber is proportionally related to left ventricular mass which can be estimated from the myocardial thickness.

This mass-spring system allows an interpretation of the correlations observed in our statistical analysis. An increased DS3 (m) implies a decrease of the absolute value of the k/m ratio. It follows that the natural frequency of the system shifts towards lower frequencies with an increase in the energy contents of this frequency range and a reduction of the energy contained in the higher frequency bands. This justifies the positive correlations between DS3 and the energy contained in the 0–15 and 15–30 Hz bands and the negative correlations between DS3 and the energy contained in the 30–45, 45–60 and 60–75 Hz bands. On the other hand, if the thickness of the posterior wall and of the septum increases, the k/m ratio increases and the energy distribution shifts towards high frequencies so the energy contained in the low frequency bands decreases (negative value of r) and the energy contained in the high frequency bands increases (positive value of r).

However, for vibrations to be generated the system must oscillate and this becomes possible if a sudden force is applied to it at the time of S3. Arevalo et al11) noticed that S3 coincides with the return to the baseline of the first derivative of the intraventricular pressure and this reflects a deceleration of the blood mass during this phase of the cardiac cycle. Craigie and Ozawa19–21) noted that the negative deflection of the first derivative of the acceleration during protodiastole is particularly deep in subjects with S3. This finding, observed only in patients with S3, suggests that at this point of the cardiac cycle, i.e. at the end of the rapid filling phase, a sudden deceleration takes place along the longitudinal axis of the ventricle. This deceleration was noticeable also by putting the accelerometer on the epicardium indicating a possible sudden intrinsic limitation of the ventricular expansion.

It is possible therefore to think that the force triggering the mass-spring system is represented by the sudden deceleration of the blood mass due to the limited longitudinal expansion of the left ventricle during the passage between the rapid filling and the slow filling phase. The force produced (F=m*a) causes the system to oscillate and the oscillation induces the acoustic vibration, the third heart sound.
ACKNOWLEDGMENTS

We are grateful to Alberto Ricci Bitti for his contribution to the preparation of the computer hardware and software and to Larry Costache for preparation of the manuscript.

REFERENCES
