Studies on Protodiastolic and Presystolic Waves in Cardiac Cycles

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AMONG THE vibrations of diastole in cardiac cycles, the third sound (S_3) and the fourth sound (S_4) have been noticed since long ago and they were considered to be expressing exactly the hemodynamic changes in the heart, and various kinds of studies have been made on them. In the past, when phonocardiographs were not yet invented, many clinical studies were made by using only stethoscope, and thus the data contained much of subjective factors. Owing to the rapid strides in electronics in recent years, phonocardiographs of high efficiency were devised. Although such modern phonocardiographs carry with them many difficult problems yet to be solved, they made it possible to some extent to catch objectively the expressions of heart sounds and murmurs. With modern phonocardiographs S_3 and S_4 are clearly recorded even in normal subjects, especially when they are young. So it becomes very difficult to draw a line between normal and pathological conditions such as the so called gallop rhythm.

The frequency ranges of S_3 and S_4 are ordinarily very low¹⁾ and their energy is relatively large. This fact suggests that S_3 and S_4 have two phases of vibrations, i.e. audible vibrations recorded in phonocardiogram (PCG) and inaudible vibrations recorded in ballistocardiogram (BCG). In this paper, the relationship between these two kinds of vibrations was studied referring to clinical data.

On the longitudinal BCG, in cases of protodiastolic gallop rhysm, the amplitude of MN wave is said to increase²⁾. On the lateral BCG, as Dock³⁾⁴⁾⁵⁾ described, using direct body pick up attached on the right side of chest wall, the

vibrations were recorded coincident with S_3 , and from the data thus obtained, he tried to explain the mechanisms of S_3 production. When we use von WITTERN'S modified sublow frequency lateral ballistocardiograph, protodiastolic vibrations are recorded coincident with S_3 (Fig. 1), and in cases of protodiastolic gallop rhysm, these vibrations increase (Fig. 2).

As for S_4 , the vibrations are recorded in BCG coincident with the sound³⁾⁴⁾. On the longitudinal BCG, these vibrations are coincident with G waves. In cases of complete A-V block, as Fig. 3 shows, the vibrations are recorded very clearly on the lateral BCG.

There is no proof that these vibrations originated in the heart, except their time relationship with S_3 and S_4 . These problems will be discussed later.

METHOD

(1) Equipment

S_3 and S_4 were recorded with the phonocardiograph made by Nihonkohden Co., Ltd. with low cut filter divided by YOSHIMURA⁶⁾, its frequency character being 15/oct. in decrement from 1,000cps to 0. Microphon was a dynamic type and was attached on the surface of the skin at apex cordis, with 100 gram weight. The amplitudes of S_3 and S_4 were calibrated with waves obtained by giving sine waves of 3 mv (peak to peak) to the input of amplifier.

BCG was recorded with the sublow frequency two dimensional ballistocardiograph made by Nihonkohden Co., Ltd. Natural oscillation of the ballistocardiograph was 0.6 cps, and the table weight was 8 gram. The frequency character of ballistocardiograph was flat from 1 to 18 cps. The calibration was obtained by using accelerator of 900 gram.

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Fig. 1. PCG and BCG in normal case. In the figure, the sign ↓ shows protodiastolic lateral wave.

↑ Fig. 2. PCG and BCG in case with protodiastolic gallop rhythm.

Fig. 3. PCG and BCG in case with complete A-V block. In the figure, sign ↓ shows pre-systolic lateral wave. →

Film speed was 2.5 or 5 cm/sec.

(2) Material

124 normal cases from 7 to 60 yrs. old (60 males and 64 females) were selected for recording normal PCG and 119 cases from 15 to 77 yrs. old (77 males and 42 females) were selected for recording normal BCG. ECG, blood pressure, heart size on chest X-ray plate, and the clinical histories of these cases were all normal.

111 cardiovascular patients from 16 to 70 yrs. old were selected for the investigations. Their ECG, chest X-ray plates and clinical courses were examined. All cases selected for the investigations showed sinus rhythm in ECG. Those who had combined cardiovascular diseases were excluded.

(3) Method for measurement

S_3 and S_4 were measured of their respective amplitude at 3 points of expirium, then the mean value was obtained and calibrated as mentioned above.

Vibrations in lateral BCG which appeared coincident with S_3 and S_4 were named by the author protodiastolic lateral wave and presystolic lateral wave respectively. These vibrations were measured at three points of expirium. As the standing waves of these vibrations were not always observed clearly, maximum amplitude of protodiastole and presystole were measured.

ECG were recorded in 12 routine leads. Diagnosis of ventricular hypertrophy was established by Sokolow and Lyon's⁷⁾⁸⁾ criteria for unipolar leads and chest leads. In this paper, all cases of ventricular hypertrophy fulfilled more than 1 criterion by them.

The heart size was measured on the chest X-ray plate and the cardiothoracic index (Transverse heart measurement/Transverse lung measurement (THM/TLM)) was calculated. The index larger than 0.5 was considered to indicate ventricular hypertrophy⁹⁾.

Clinical histories were recorded precisely, but as the complaints in each case were variable, the comparison of clinical histories was considered meaningless. Thus, in this paper, the history of congestive heart failure was selected as the clinical manifestation of heart diseases.

RESULTS

(1) Normal cases

a) Amplitude of S_3

Fig. 4 shows the relationship between the amplitude ratio of S_3 ($=S_3/\text{Calibration}$) and age. Decrease in amplitude was observed with advancing age, indifferent to sex. The amplitude ratio of S_3 in normal subjects was below 1.0 in the group less than 25 yrs. old, while it was below 0.5 in the group over 26 yrs. old.

Fig. 4. Relationship between S_3 and age in normal subjects.

b) Amplitude of protodiastolic lateral wave

Fig. 5 shows the relationship between the amplitude of protodiastolic lateral wave and age. The amplitude of protodiastolic wave in normal cases was below 60 gram, indifferent to age and sex.

c) Amplitude of S_4

Fig. 6 shows the relationship between the amplitude ratio of S_4 ($=S_4/\text{Calibration}$) and age. Decrease in amplitude was observed with ageing. But such tendency was not so clear as in the amplitude ratio of S_3 . The amplitude ratio of S_4 in normal subjects was below 0.8 under 40 yrs. old, while it was below 0.4 in the group over 41 yrs. old.

d) Amplitude of presystolic lateral wave

Fig. 7 shows the relationship between the amplitude of presystolic lateral wave and age. The amplitude of presystolic lateral wave in normal cases was below 50 gram, indifferent to age and sex.

From the data of normal subjects, the normal values of these vibrations were determined.

Fig. 5. Relationship between protodiastolic lateral wave and age in normal subjects.

Fig. 7. Relationship between presystolic lateral wave and age in normal subjects.

Fig. 6. Relationship between S_4 and age in normal subjects.

S_3 : below 1.0 under 25 yrs. :

below 0.5 over 26 yrs.

S_4 : below 0.8 under 40 yrs. :

below 0.4 over 41 yrs.

Protodiastolic lateral wave : below 60 gram.

Presystolic lateral wave : below 50 gram.

(2) Cases of cardiovascular diseases

a) S_3 and protodiastolic lateral wave

S_3 was measured in 93 among 119 cases of cardiovascular diseases. S_3 could not be distinguished clearly from diastolic murmurs in cases of aortic insufficiency and mitral stenosis ; therefore such cases were excluded.

Fig. 8 shows the relationship between S_3 and protodiastolic lateral wave. By drawing lines at the upper limits of normal ranges of S_3 and those of diastolic lateral waves respectively, four quadrants are obtained. These are :

I : accentuated S_3 with accentuated protodiastolic lateral wave.

II : accentuated S_3 with normal protodiastolic lateral wave.

III : normal S_3 and normal protodiastolic lateral wave.

IV : normal S_3 and accentuated protodiastolic lateral wave.

Fig. 8. Relationship between S_3 and protodiastolic lateral wave in cases with cardiovascular diseases.

Table I shows numbers of final diagnosis of cardiovascular patients in each quadrant. Table II shows the results of ECG findings, heart size on chest X-ray plate, and clinical findings in each quadrant.

In quadrant I, enlargement of heart size on chest X-ray plate, abnormal ECG, and severe clinical conditions were observed at the highest percentage.

Only 7 cases were included in quadrant II. They were 2 cases of aortic insufficiency, 3 of Basedow's disease, and 2 of ventricular septal

TABLE I NUMBER OF CASES WITH CARDIOVASCULAR PATIENTS IN FOUR QUADRANTS

Quadrant	I	II	III	IV	Total
Diag.					
MS	4	0	2	2	8
MSI	3	0	1	0	4
MI	4	0	3	1	8
AS	0	0	0	2	2
ASI	2	0	0	0	2
AI	7	2	5	4	18
ASD	2	0	2	3	7
VSD	3	2	5	4	14
PDA	2	0	1	1	4
PS	2	0	1	2	5
Pul. dil.	1	0	0	0	1
Fallot	0	0	1	1	2
Basedow	0	3	0	2	5
Hypertension	0	0	2	0	2
PMD	0	0	2	0	2
Coarct.	0	0	2	0	2
Aort. arch.	0	0	1	0	1
Unknown	3	0	0	2	5
Total	33	7	28	24	92

Pul. dil.; Idiopathic pulmonary dilatation.

PMD; Progressive muscle dystrophy.

Coact.; Coarctation of the aorta.

Aort. arch.; Aortic arch syndrome.

defect. These cases were almost mild in clinical conditions.

Quadrant III included various kinds of diseases. In the majority of cases in this group, size of the heart and ECG were normal. Only 2 cases (7.4%) had history of congestive heart failure. They were aortic insufficiency with subacute bacterial endocarditis and progressive muscle dystrophy (PMD), and both of these cases were small women of 40 yrs.

Quadrant IV included severe clinical conditions, and the percentage of abnormal ECG and enlargement of heart size were highest next to that in the quadrant I. It was very interesting to notice that cases with right ventricular hypertrophy (RVH) in ECG were found at the highest percentage in this quadrant.

TABLE II THE RESULTS OF ECG FINDINGS, HEART SIZE ON CHEST X-RAY PLATE AND CLINICAL CONDITIONS IN FOUR QUADRANTS

Quadrant	THM/TLM		ECG findings						Cong. heart failure	
	$0.5 \geq$	$0.5 <$	Normal	RVH	LVH	BVH	ST-T abnorm.	other abnorm.	+	-
I	11%	89%	13.5%	21.6%	21.6%	8.2%	18.8%	16.3%	41.0%	59.0%
II	75	25	83.5	0	16.5	0	0	0	0	100
III	83	17	57.1	21.4	10.7	3.6	3.6	3.6	7.4	92.6
IV	60	40	27.3	31.9	13.6	0	13.6	13.6	33.3	66.7

Fig. 9 shows the relationship between the amplitude of protodiastolic lateral wave and ECG findings. In the figure, the sign ○ shows the accentuation of S_3 . In cases with left ventricular hypertrophy (LVH) in ECG, accentuation of S_3 was seen even when the amplitude of protodiastolic lateral wave was rather low compared

with cases with RVH.

Fig. 10 shows the amplitude of protodiastolic lateral wave and the final diagnosis of cardiovascular patients. No remarkable relationship between them was found.

b) S_4 and presystolic lateral wave

Fig. 11 shows the relationship between S_4 and

Fig. 9. Relationship between ECG findings in each cardiovascular patient and protodiastolic lateral wave.

Fig. 10. Amplitude of protodiastolic lateral wave in each cardiovascular patient.

Fig. 11. Relationship between S_4 presystolic lateral wave in cases with cardiovascular diseases.

presystolic lateral waves in 94 cases of cardiovascular diseases. Four quadrants are obtained by drawing lines at the upper limits of normal ranges of S_4 and those of presystolic lateral wave respectively. These are:

- A: accentuated S_4 with accentuated presystolic lateral wave.
- B: accentuated S_4 with normal presystolic lateral wave.
- C: normal S_4 with normal presystolic lateral wave.
- D: normal S_4 with accentuated presystolic lateral wave.

Table III shows the numbers of final diagnosis of cardiovascular patients in each quadrant. Table IV shows the results of ECG findings, heart size on chest X-ray plate, and clinical findings in each quadrant.

In quadrant A, many cases with abnormal ECG findings and enlargement of heart size were observed, but only one case (12.5%) had clinical history of congestive heart failure.

TABLE III NUMBERS OF CASES WITH CARDIOVASCULAR PATIENTS IN FOUR QUADRANTS

Quadrant	A	B	C	D	Total
Diag.					
MS	1	1	6	2	10
MSI	0	0	1	1	2
MI	1	1	5	1	8
AS	0	0	1	1	2
ASI	0	2	1	1	4
AI	0	4	10	5	19
ASD	0	0	6	1	7
VSD	0	4	5	5	14
PDA	1	0	1	1	3
PS	0	0	5	0	5
Pul. dil.	0	1	0	0	1
Fallot	0	0	2	0	2
Basedow	3	2	0	0	5
Hypertension	0	1	1	0	2
PM D	0	0	2	0	2
Coarct.	0	0	2	0	2
Aort. arch.	0	0	1	0	1
Unknown	2	1	1	1	5
Total	8	17	50	19	94

TABLE IV THE RESULTS OF ECG FINDINGS, HEART SIZE ON CHEST X-RAY PLATE AND CLINICAL CONDITIONS IN FOUR QUADRANTS

Quadrant	THM/TLM		ECG findings						Cong. heart failure	
	$0.5 \geq$	$0.5 <$	Normal	RVH	LVH	BVH	ST-T abnorm.	other abnorm.	+	-
A	16.5%	83.5%	22.2%	33.4%	22.2%	0 %	11.1%	11.1%	12.5%	87.5%
B	25.0	75.0	13.3	20.0	13.3	6.7	26.7	20.0	23.5	76.5
C	65.7	34.3	42.3	26.9	13.3	3.9	9.6	3.8	23.0	77.0
D	53.5	46.5	25.0	25.0	25.0	0	20.0	5.0	37.5	62.5

In quadrant B, patients with abnormal ECG were found at the highest percentage among four quadrants.

In quadrant C, patients with normal ECG and normal heart size were found at the highest percentage.

In quadrant D, numbers of patients with normal ECG findings and normal heart size were highest next to those in quadrant C. On the other hand the clinical history of congestive heart failure was observed at the highest percentage in this group.

Fig. 12 shows the amplitude of presystolic lateral wave in each of cardiovascular diseases. In this figure, the sign o shows the accentuation of S_4 and the sign ■ shows the cases of mitral stenosis with presystolic murmur. No marked relationship between them was found.

DISCUSSION

(1) Fundamental consideration

Protodiastolic and presystolic waves in sub-low frequency lateral BCG will be discussed in relation to S_3 and S_4 , referring to the clinical data.

Protodiastolic and presystolic waves were observed coincident with the appearance of S_3 and S_4 . However, this fact does not necessarily show that protodiastolic and presystolic lateral waves originated from the heart itself. Now, discussion will be made about the relationship between these waves.

It is believed that G wave in longitudinal BCG appears in close connection with the auricular contraction¹⁰⁾¹¹⁾, and H wave appears at the time of ventricular contraction¹²⁾. The beginning of ventricular contraction coincides with the top of H wave. On the other hand, as pointed out by NICKERSON¹³⁾, BROWN²⁾, DOCK³⁾,

Fig. 12. Amplitude of presystolic lateral wave in each cardiovascular patient.

STARR¹⁴⁾, and SHIMIZU¹⁵⁾, H wave seems to have a certain component of auricular contraction. NOODERGRAAF¹⁰⁾¹⁵⁾ observed the pressure patterns of main arteries in all parts of human body, and measured the changes of blood distribution. Then, he calculated the first derivatives of this pattern, and made the synthesized waves, which were similar to the ultralow frequency BCG patterns recorded by SCARBOROUGH¹⁷⁾. In his work, NOODERGRAAF drew curves from G wave to H wave referring to the changes of blood distribution in the heart, and he pointed out that G wave appeared in connection with auricular contraction. L, M and N waves appear at the time of ventricular rapid filling, but these patterns are changed by the peripheral vascular attitude, as well as by the ventricular conditions¹⁸⁾. Dock believed that the vibrations in protodiastole and presystole on longitudinal and lateral BCG were produced by the same mechanisms of production of S_3 and S_4 .

In my data, presystolic lateral wave appeared almost coincident with the appearance of G wave in longitudinal BCG, and immediately after P wave in ECG, while protodiastolic lateral wave appeared directly after S_3 . The character of the protodiastolic lateral wave was not always closely connected with MN waves in longitudinal BCG.

REISSMAN¹⁹⁾ used torsion ballistocardiograph and observed lateral vibrations at the appearance time of S_3 and S_4 . The ballistocardiograph used

in my work is a kind of torsion ballistocardiograph. Therefore, as REISSMAN pointed out, organs which are considered to be producing lateral vibrations, are asymmetrical parts of arterial system in longitudinal plane. The asymmetrical parts in this plane are the heart and the aortic arch.

From the discussion above, the vibrations in protodiastole and presystole in lateral BCG may possibly originate from the heart and so discussions will be permissible about the relationship between these vibrations and S_3 or S_4 .

The next problem to be discussed is the calibration of PCG. This problem was hitherto discussed by many authors and yet may not be solved in near future because of the difficulties inherent in it. Concerning S_3 and S_4 , the increase of their amplitude is generally accompanied by the increase of frequency. In most cases selected for my investigations, increase of amplitude could be expressed as increase of frequency. But, in some cases, the expression of increase in frequency was very difficult, because many subjective factors may interfere with the determination of degrees of increase in frequency.

Thus, in this paper, I tried to express the intensity of S_3 and S_4 as the height of amplitude in each case, as stated before. In this method for calibration, specific characters of microphone are excluded. Using the same microphone, and under the same conditions, the comparison of

S_3 and S_4 amplitude in each case is considered to be significant to some extent. However, these data do not express the whole characters of S_3 and S_4 , but they are significant only when this phonocardiograph and microphone are used.

(2) Consideration on normal data

i) S_3 and protodiastolic lateral wave

As mentioned above, the amplitude of S_3 in normal cases decreases with aging, while protodiastolic lateral wave has the same amplitude indifferent to the age. S_3 can be heard in almost all young people, while the percentage of cases with audible S_3 decrease with advancing age. This fact is in accordance with the previous study on Japanese people²⁰⁾. These data suggest that the low frequency vibrations originate always in the heart cavity, and that the transmission of relatively high frequency vibration becomes impaired with aging.

ii) S_4 and presystolic lateral wave

S_4 decreases in amplitude with aging, while presystolic lateral wave remains always the same. The reason for this is considered to be the same as that in S_3 , just mentioned above.

To determine normal values for those vibrations is very difficult, because the mode of transmission of heart sound is different in each case. And it seems to be meaningless to observe the mutual relations between S_3 and protodiastolic lateral wave or between S_4 and presystolic lateral wave.

Therefore, in this paper the normal ranges are defined according to my own criteria for the following discussion. However, some irrationalities may be pointed out in such criteria. For example, in cases of acquired heart disease, the amplitude of S_3 may increase compared with that in normal condition. According to my own criteria, the increase in such cases is not always expressed as the pathological conditions.

(3) Consideration on cardiovascular diseases

i) S_3 and protodiastolic lateral wave

From the criteria of my own for normal subjects, it was expected that quadrant I included severe cases, while quadrant III included rather mild cases, and actually the data proved to be as expected. On the other hand, cases in quadrant IV included those which were to be classified as being between I and III in severity. This fact clearly shows that the pathological changes

in intracardiac phenomena are most marked in cases in quadrant I, then those in quadrant IV and finally those in quadrant III.

Cases in quadrant IV included those which were known as not easily accompanied by accentuated S_3 . For example, many cases of mitral stenosis, which generally have no accentuated S_3 , may be included in quadrant IV. On the other hand, as Fig. 9 shows, increase in protodiastolic lateral wave was observed in cases with ventricular hypertrophy in ECG. Especially, in cases with RVH, protodiastolic lateral wave was accompanied by accentuated S_3 only when its amplitude became higher than that in cases with LVH. As almost all cases of RVH in quadrant IV were those with mitral stenosis, it is highly probable that the vibrations contain mainly those originated in right ventricle. This fact shows that S_3 originating from right ventricle is not easily accentuated, while the protodiastolic lateral wave changes according to cardiac conditions.

It is very difficult to explain the case in quadrant II, but as their clinical conditions are rather mild, those cases are considered to be equivalent to those with accentuated S_3 without prognostic significance²¹⁾.

Thus, the accentuation of protodiastolic lateral wave is considered by the author to have prognostic significance. The protodiastolic gallop rhythm with clinical significance or its pre-stage may be determined by measuring S_3 and protodiastolic lateral wave. These facts seem to be useful for clinical purposes and wide application is expected.

ii) S_4 and presystolic lateral wave

The relationship between S_4 and presystolic lateral wave is very complicated. Quadrant A, in which S_4 and presystolic lateral wave were both accentuated, contains many cases with abnormal ECG and enlargement of heart size on X-ray plate, but these cases were relatively mild in clinical conditions. On the contrary, quadrant C, in which S_4 and presystolic wave were both normal, contains many patients with normal ECG and normal heart size, and yet their clinical conditions were not always mild. These facts suggest that as for S_4 , its accentuation has no relationship with clinical conditions. So in this paper, discussion will be done referring only to

ECG findings and heart size on X-ray plate.

Quadrant B contains many cases with abnormal findings in ECG and X-ray plate. Therefore, S_4 accentuation precedes the accentuation of presystolic lateral wave.

McKUSICK²²⁾ and UEDA et al.²¹⁾²³⁾ pointed out that S_4 accentuation is caused by systolic overloading in the heart. But the author of this paper could not confirm such relationship between them. This may be due to the difference in criteria used.

On the other hand, in cases of mitral stenosis, in which the auricular function is accentuated, presystolic lateral wave is not accentuated.

From these facts, it may be inferred that the mechanism of production of S_4 and of presystolic lateral wave is very complicated and that many factors are concerned in it.

SUMMARY

The relationship between heart sounds S_3 and S_4 in PCG on one hand and vibrations in lateral BCG on the other were studied referring to the clinical data.

According to the author the protodiastolic lateral wave in BCG is clinically useful, while the presystolic lateral wave is not.

The conclusions on protodiastolic waves are as follows.

- 1) S_3 decreased its amplitude with aging in normal cases.
- 2) Vibrations always originated in the heart, and decrease in amplitude of S_3 showed only the decrease in the capability of transmission.
- 3) Almost all cases with accentuated S_3 were accompanied by accentuated protodiastolic lateral wave and their clinical conditions were very severe.
- 4) The cases with accentuated protodiastolic lateral wave, without accentuated S_3 , were considered to be the pre-stage of protodiastolic gallop rhythm and they had clinical significance.
- 5) Accentuated S_3 without accentuated protodiastolic lateral wave was not clinically significant.

- 6) Protodiastolic lateral wave originated from right ventricle was accompanied by accentuated S_3 , only when its amplitude became very large.

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