VECTORCARDIOGRAPHIC STUDY ON LEFT VENTRICULAR HYPERTROPHY IN SPONTANEOUSLY HYPERTENSIVE RATS

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To observe cardiac changes in spontaneously hypertensive rats (SHR) functionally, the vectrocardiographic approach was tried, applying the Takayasu lead system to rats. This vectrocardiogram (VCG) was shown to be sufficiently good to detect left ventricular hypertrophy (LVH) in SHR.

VCG in SHR showed specific features, some of which were left upward deviation of the maximum QRS vector in the frontal plane, an increased magnitude of the maximum spatial QRS vector, and prolongations of such indices as the QRS duration, time to the maximum spatial QRS vector and QT interval with abnormal ST-T changes. The P wave of SHR in the X scalar electrocardiogram, lower and wider than that of Wistar-Kyoto rats may also be a significant feature of LVH in SHR.

The angle of the maximum QRS vector in the horizontal plane was not proven to be a suitable index of LVH in SHR.

Most of the histometrical findings were closely correlated to blood pressure.

Some of the vectrocardiographic findings were significantly correlated both to blood pressure and to some of the characteristic findings of LVH, such as the weights of the heart and the left ventricle and so forth.

This experiment also indicated that LVH in SHR was not limited only to quantitative myocardial hypertrophy. It also seemed to be related to reversible or irreversible qualitative changes of coronary arteries or myocardium, such as myocardial fibrosis.

This vectrocardiographic method was shown to be useful in obtaining various information about the cardiovascular system in rats, especially in SHR, and it seemed to be helpful for further understanding hypertensive cardiac diseases in humans.

Key Words:
Vectrocardiogram (VCG)
Takayasu lead system
Left ventricular hypertrophy (LVH)
Maximum spatial QRS vector
Left axis deviation
ST-T changes
QT interval
Myocardial fibrosis
Coronary arterial wall thickning
Cardiothoracic ratio
Spontaneously hypertensive rats (SHR)

ELECTRO- or vectrocardiographic studies of left ventricular hypertrophies (LVH) in rats have been reported up to the present by some researchers[1,2] In these reports experimental hypertensive rats, such as renal hypertensive rats or potassium-deficiencied rats, were used as models of LVH. *Sambhi and White*[1] using potassium-deficiencied rats, described the exclusive presence of the backward orientation of the spatial QRS vector, a left axis rotation of

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the P vector, an increase in the QRS duration, and so forth, as the electro- and vectrocardiographic indices of LVH. However, the method of Grand[3] was used to determine the orientation of the spatial vector. *Uhley and Proctor*[2] recording vectrocardiograms of renal hypertensive rats by three axes (superoinferior, posteroanterior, and right to left axes), emphasized significant large amplitudes of mean QRS vectors and R waves in the superoinferior axis.

In spontaneously hypertensive rats (SHR),[4,5] which are generally regarded as the best model so far for essential hypertension in man,[6,7] cardiac hypertrophy is one of the most preponderant hypertensive complications.[5] Cardiac hypertrophy has been observed morphologically and studied biochemically;[8-10] but not electro- or vectrocardiographically. Not only cardiac hypertrophies but also myocardial infarctions are sometimes found in SHR. SHR seem to be suitable models for studies on cardiac complications of hypertension. However, some new, if possible simpler method has been required to detect these cardiac abnormalities functionally, and to follow up these changes according to the ageing process.[11]

We report in this paper about our application of the vectrocardiogram for detecting cardiac hypertrophies in SHR, especially in stroke-prone SHR, the new substrain with severe hypertension.[12,13]

TABLE I BODY WEIGHT AND BLOOD PRESSURE OF WK AND SHR

Group	*No. of Animals*	*Age (days)*	*Body Weight (g)*	*Blood Pressure (mmHg)*
WK	*5*	*124 ± 0*	*348 ± 16*	*123 ± 7*
SHR	*5*	*164 ± 7***	*326 ± 10*	*240 ± 4***

WK: Wistar-Kyoto rats
SHR: Spontaneously Hypertensive Rats
Values represent mean ± SE.
***: Statistically significant difference from WK ($p < 0.01$)*

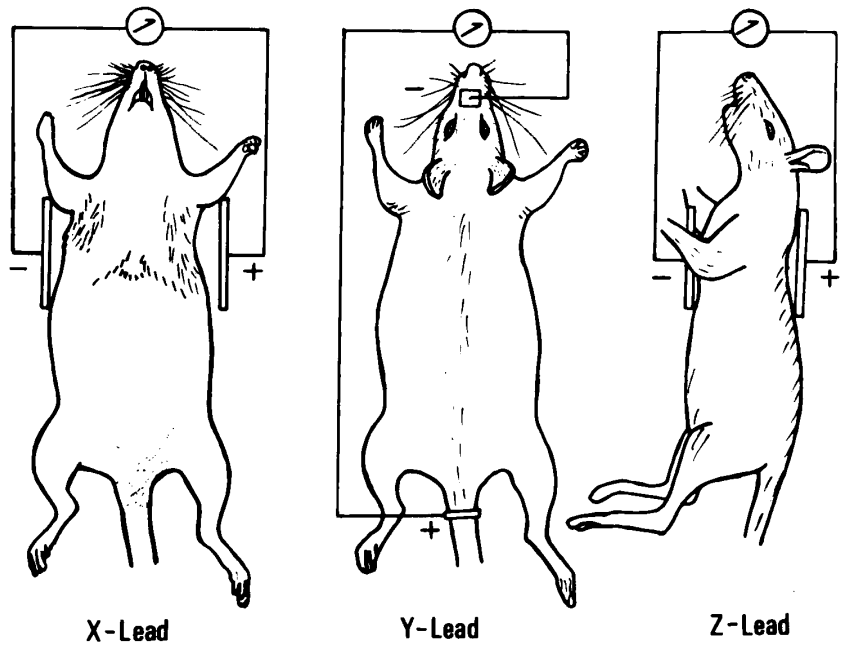

Fig.1. The Takayasu lead system applying to rats: Two small electrodes and 4 large electrodes make orthogonal 3 axes, namely, from right to left (X-axis), from up to down (Y-axis), and from front to back (Z-axis).

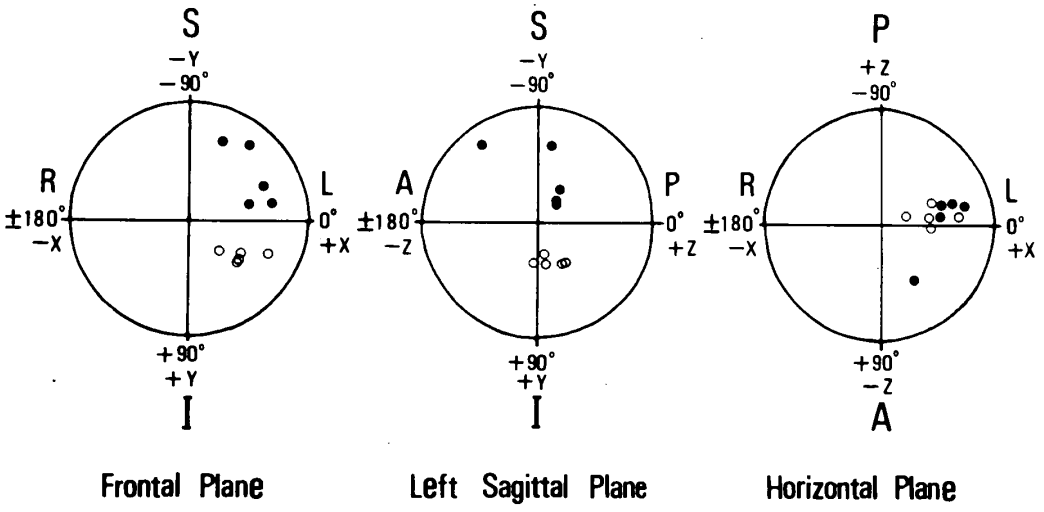

Fig.2. Polarities of the vectrocardiogram and the relative positions of the tips of the maximum QRS vectors in each plane: The polarities of the vectrocardiogram are set the same as those of the Frank lead system. S: Superior, I: Inferior, R: Right, and L: Left. The white spots are the tips of the vectors in WK; the black spots are the tips of the vectors in SHR.

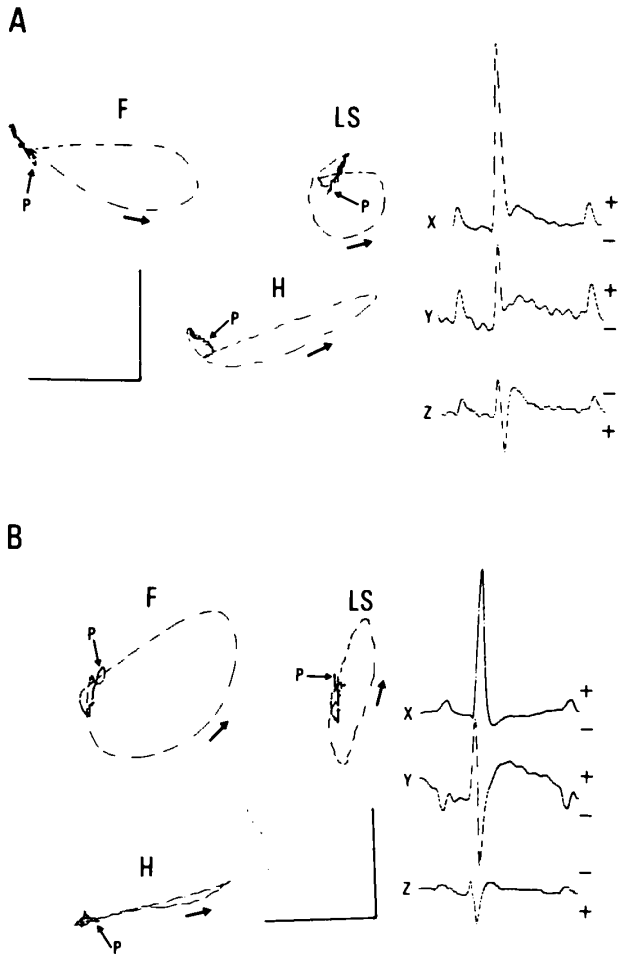

Fig.3. A and B represent typical vectrocardiograms of WK (A) and SHR (B). Calibration: 1 mV.

Materials and Methods

In the preliminary experiment, we tried to give vectrocardiogram (VCG) and electrocardiogram (ECG) to about 150 rats from 3 groups – stroke-prone SHR (SHRSP) and stroke-resistant SHR (SHRSR), which developed stroke spontaneously over 80% and less than 10% respectively, and to Wistar-Kyoto (WK) rats from which SHR had been derived.

A total of 10 rats were studied for cardiac hypertrophies. These 10 rats consisted of 2 groups – 5 SHRSP and 5 WK. They were all males aged from 124 to 172 days and maintained at the Department of Pathology, Kyoto University, under a standard laboratory condition[12] (Table I).

Indirect tail blood pressures were measured without anesthesia by a pulse-pick-up method.[14]

When applying VCG to rats, various systems for VCG leading were tried in our preliminary experiments. The Frank lead system was initially tried, but it was found to be difficult to fix multiple leads on the movable skin of the rats. Among various lead systems the Takayasu lead system[15] was confirmed to be the most reliable one for VCG recording in small animals such as rats.

In the Takayasu lead system, 6 electrodes consisting of 2 small electrodes and 4 large electrodes (placed at the front and back, right and left sides of chest) made orthogonal 3 axes –

TABLE II QRS VECTOR IN EACH PLANE

Group	No. of Animals	Plane	Maximum QRS Vector		Incidence of Loop Patterns			
			Means of Magnitudes (mV)	Means of Angles (degree)	CCW	Figure-eight	CW	Complicated
WK	5	Frontal	1.35 ± 0.14	36.8 ± 4.0	4	1	0	0
		Sagittal	0.92 ± 0.06	74.2 ± 7.1	3	2	0	0
		Horizontal	1.11 ± 0.17	−10.2 ± 4.5	4	1	0	0
SHR	5	Frontal	1.74 ± 0.12	−34.4 ± 11.0**	5	0	0	0
		Sagittal	1.13 ± 0.31	−69.2 ± 15.9**	2	1	1	1
		Horizontal	1.50 ± 0.10	1.2 ± 15.0	3	2	0	0

CCW: Counterclockwise rotation, Figure-eight: Figure-eight pattern,
CW: Clockwise rotation, Complicated: Complicated pattern,
KW and SHR: Refer to Table I.
Values in the Maximum QRS Vector represent mean ± SE.
***: Statistically significant difference from WK ($p < 0.01$)*

X,Y,Z –, which configurated frontal, sagittal, and horizontal planes (Fig. 1). Four large electrode plates were made from usual metal plates of electrocardiography, and their sizes were 3x4.5 square cm for the frontal, and 2x2 square cm for the others.

In this experiment, the vectrocardiographic apparatus of S-3013 (Nihonkohden) was used. The polarity of VCG was set the same as that in Frank's method (Fig. 2).

In order to get a close attachment of the electrodes to the skin, the hair of the rat was neatly cut, and a cotton mat was then placed between the skin and the plate. Rats under nembtal anesthesia (40 mg/g, i.p.) were set to the VCG equipment in the prone position, and they were almost fixed by four transparent plastic walls with large lead plates around the trunk.

Before or after the VCG recording, ECG by extremity leads and by 3 or 4 chest leads were taken to supplement VCG.

After VCG was taken repeatedly to confirm reproduciblity, all rats were sacrificed by decapitation. The weight of the heart, and the weight, length and thickness of the left ventricle and so forth were measured by slide calipers immediately after sacrifice.

In addition, 2 groups of 10-month-old male SHRSP and WK, respectively 5 and 4 in each group, were examined by chest X-ray photography in prone position to determine the cardiothoracic ratio, under X-ray condition of 40,000 V, 0.1 sec.

The histological sections of the hearts from the rats of all experimental groups were prepared by routine techniques, and the myocardium and coronary arteries were examined microscopically.

Results

Typical vectrocardiograms of SHR and WK are shown in Fig. 3 and vectrocardiographic findings are summarized in Tables II - V.

QRS Loop Patterns

Frontal Plane – Nine out of 10 rats of both groups indicated counterclockwise (CCW) QRS rotations. The remaining showed a figure-eight pattern. No clockwise (CW) rotations were observed. The shapes of these QRS loops generally tended to elliptically elongated, and sometimes they were oval.

Left Sagittal Plane – CCW QRS rotations were noted in 5 cases (3 and 2 in WK and SHR, respectively). Figure-eight patterns were observed in 3 cases (2 and 1 in WK and SHR, respectively). One CW rotation was noted only in SHR.

Horizontal Plane – CCW rotations were seen in 7 cases of all rats (4 and 3 in WK and SHR, respectively). Figure-eight patterns were seen in 3 (1 and 2 in WK and SHR, respectively). CW patterns appeared in one case of SHR. Loop configurations appeared to be more elongated in WK than in SHR.

TABLE III MAXIMUM SPATIAL QRS VECTOR

Group	No. of Animals	Magnitude (mV)	QRS Duration (msec)	Time to max. Spatial QRS vector (msec)
WK	5	1.43 ± 0.11	31.3 ± 0.8	13.2 ± 0.2
SHR	5	1.87 ± 0.15*	34.5 ± 1.0*	15.9 ± 0.7**

WK and SHR: Refer to Table I.
Values represent mean ± SE.
**, **: Statistically significant difference from WK*
(: 0.01 < p < 0.05, **: p < 0.01)*

TABLE IV MAXIMUM SPATIAL P VECTOR

Group	No. of Animals	Magnitude (mV)	Elevation (degree)	Azimuth (degree)	P Duration (msec)
WK	5	0.28 ± 0.03	54.4 ± 6.4	14.4 ± 11.6	25.8 ± 1.3
SHR	5	0.20 ± 0.02	40.2 ± 25.2	33.8 ± 13.8	32.2 ± 2.1*

WK and SHR: Refer to Table I, Values represent mean ± SE.
**: Statistically significant difference from WK (0.01 < p < 0.05)*

TABLE V PQ AND QT INTERVALS

Group	No. of Animals	PQ Interval (msec)	QT Interval (msec)	Puls Rate per min
WK	5	49.4 ± 1.6	70.7 ± 7.8	362 ± 15
SHR	5	48.5 ± 1.8	106.8 ± 3.6**	357 ± 5

WK and SHR: Refer to Table I. Values represent mean ± SE.
***: Statistically significant difference from WK (p < 0.01)*

Magnitude of Maximum QRS Vector

Frontal Plane – Magnitudes of maximum QRS vectors ranged from 0.90 mV to 1.81 mV (mean 1.35 mV) in WK and from 1.33 mV to 2.05 mV (mean 1.74 mV) in SHR.

Left Sagittal Plane – Values of each group were from 0.72 mV to 1.05 mV (mean 0.92 mV) in WK and from 0.53 to 2.05 mV (mean 1.13 mV) in SHR.

Horizontal Plane – The ranges of the magnitudes of maximum QRS vectors were from 0.59 mV to 1.66 mV (mean 1.11 mV) in WK and from 1.33 mV to 1.85 mV (mean 1.50 mV) in SHR.

The values of these magnitudes indicated that in both groups the mean values were larger in the frontal plane than in the other two planes, and that SHR had larger mean values than WK in all three planes.

Angle of Maximum QRS Vector

Frontal Plane – The ranges of the angles of maximum QRS vectors varied from 23° to 46° (mean 36.8°) in WK, and from −68° to −12° (mean −34.4°) in SHR. The angles were all positive in WK, and all negative in SHR. The QRS vectors deviated left upward in SHR, -that is, a left axis deviation was commonly noted.

Left Sagittal Plane – Angles were oriented from 57° to 93° (mean 74.2°) in WK, and from −126° to −40° (mean −69.2°) in SHR. The angles were all positive in WK, and contrarily all negative in SHR.

TABLE VI THE WEIGHT AND LENGTH OF THE HEART, AND THE WEIGHT OF THE LEFT VENTRICLE

Group	No. of Animals	Heart Weight (g)	Heart Weight per g BW $\times 10^{-3}$	Heart Length (mm)	Heart Length per g BW $\times 10^{-3}$	LV Weight (g)	LV Weight per g BW $\times 10^{-3}$	LV Weight per RV Weight $\times 10^{-3}$
WK	5	1.08 ± 0.04	3.10 ± 0.10	13.9 ± 0.40	4.56 ± 0.25	0.66 ± 0.03	2.17 ± 0.06	3.33 ± 0.41
SHR	5	1.41 ± 0.04**	4.31 ± 0.10**	15.5 ± 0.20**	4.98 ± 0.10	1.03 ± 0.04**	3.30 ± 0.13**	5.70 ± 0.33**

LV: Left ventricle, RV: Right ventricle, BW: Body weight, WK and SHR: Refer to Table I.
*Values represent mean ± SE. **: Statistically significant difference from WK ($p < 0.01$)*

TABLE VII THE THICKNESS OF THE VENTRICULAR WALLS

Group	No. of Animals	Thickness of Left Ventricular Wall				Thickness of Right Ventricular Wall (mm)
		Septum (mm)	Lateral (mm)	Anterior (mm)	Posterior (mm)	
WK	5	2.1 ± 0.1	2.4 ± 0.1	2.2 ± 0.1	2.0 ± 0.2	1.0 ± 0.0
SHR	5	2.8 ± 0.1**	3.1 ± 0.1**	3.0 ± 0.1**	2.9 ± 0.1**	1.0 ± 0.0

WK and SHR: Refer to Table I.
*Values represent mean ± SE. **: Statistically significant difference from WK ($p < 0.01$)*

TABLE VIII CORRELATION AMONG THE VECTORCARDIOGRAPHIC FINDINGS, THE BLOOD PRESSURE AND THE HISTOMETRICAL FINDINGS — THE WEIGHT AND LENGTH OF THE HEART AND THE LEFT VENTRICLE

	Blood Pressure	*Heart Weight*	*Heart Weight per BW*	*Heart Length*	*Heart Length per BW*	*LV Weight*	*LV Weight per BW*	*LV Weight per RV Weight*
Angle								
Frontal	*−0.890***	*−0.734**	*−0.806***	*−0.685**	—	*−0.779***	*−0.734**	*−0.711**
Sagittal	*−0.911***	*−0.813***	*−0.882***	*−0.774***	—	*−0.830***	*−0.801***	*−0.699**
Horizontal	—	—	—	—	—	—	—	—
Magnitude of max. spatial QRS vector	*0.685**	—	—	—	—	—	—	—
QRS Duration	*0.645**	—	*0.718**	—	*0.691**	*0.670**	*0.804***	*0.674**
Time to max. spatial QRS vector	*0.827***	*0.835***	*0.834***	*0.698**	—	*0.857***	*0.841***	*0.771***
QT Interval	*0.909***	*0.912***	*0.935***	*0.777***	—	*0.951***	*0.931***	*0.831***
Blood Pressure	/	*0.903***	*0.921***	*0.849***	—	*0.947***	*0.886***	*0.925***

*LV: Left ventricle, RV: Right ventricle, BW: Body weight. *, **: Statistically significant (*: $0.01 < p < 0.05$, **: $p < 0.01$)*
—: Not statistically significant

TABLE IX CORRELATION AMONG THE VECTORCARDIOGRAPHIC FINDINGS, THE BLOOD PRESSURE AND THE THICKNESS OF THE LEFT VENTRICLE

	Part of Left Ventricular Wall			
	Septum	*Lateral*	*Anterior*	*Posterior*
Angle				
Frontal	*−0.745**	*−0.767***	*−0.825***	*−0.818***
Sagittal	*−0.757**	*−0.814***	*−0.873***	*−0.916***
Horizontal	—	—	—	—
Magnitude of max. spatial QRS vector	—	—	—	—
QRS Duration	—	—	—	—
Time to max. spatial QRS vector	*0.700**	*0.957***	*0.557**	*0.633**
QT Interval	*0.821***	*0.788***	*0.775***	*0.799***
Blood Pressure	*0.884***	*0.902***	*0.824***	*0.808***

**, **: Statistically significant (*: $0.01 < p < 0.05$, **: $p < 0.01$)*
—: Not statistically significant

Horizontal Plane – Angles ranged from −22° to 2° (mean −10.2°) in WK and from −18° to 61° (mean 1.2°) in SHR. Thus there was no significant difference between the two groups.

These magnitudes and angles of maximum QRS vectors in each plane are plotted in Fig. 2.

Spatial QRS Vector

Measurements of spatial QRS vectors are summarized in Table III. The averages of the magnitudes of maximum spatial QRS vectors were larger in SHR than in WK (1.43 mV in WK and 1.87 mV in SHR).

QRS duration was measured. Particularly in SHR, it was difficult to determine the ST junction as clearly as in humans. Hence we defined QRS duration as the duration from the initiation of the Q wave to the lowest point of the S wave in the X scalar electrocardiogram (ECG). In addition to the QRS duration, the duration between the initiation of the Q vector and maximum spatial QRS vector – time to maximum spatial QRS vector – was measured. The averages of time to the maximum spatial QRS vector were 13.2 msec in WK and 15.9 msec in SHR. Both averages were significantly larger in SHR than in WK.

Spatial P Vector

Unlike the T vector, the P vector was much more predominantly observed (Fig. 3). The averages of the durations of the maximum spatial P vectors were 25.8 msec in WK and 32.2 msec in SHR. The directions of the maximum spatial P vectors were almost the same in both groups, namely in the left anterior inferior direction. However, in SHR both directions of maximum P and QRS vectors made almost right angles in the frontal plane.

In SHR, the magnitude of the maximum spatial P vector was slightly smaller, but the duration was significantly longer than in WK. PQ durations did not differ significantly from each other (Tables IV and V).

ST-T Vector

In the ECG of rats, the T wave appeared to arise immediately from the ST-junction without an isoelectric ST segment. The ST and T vector (ST-T vector) in the vectrocardiogram (VCG) of rats usually did not shape a closed loop, but rather a widely-opened loop corresponding to a low and undefind ST and T wave (ST-T wave) in ECG.

The ST-T vector in SHR, particularly in

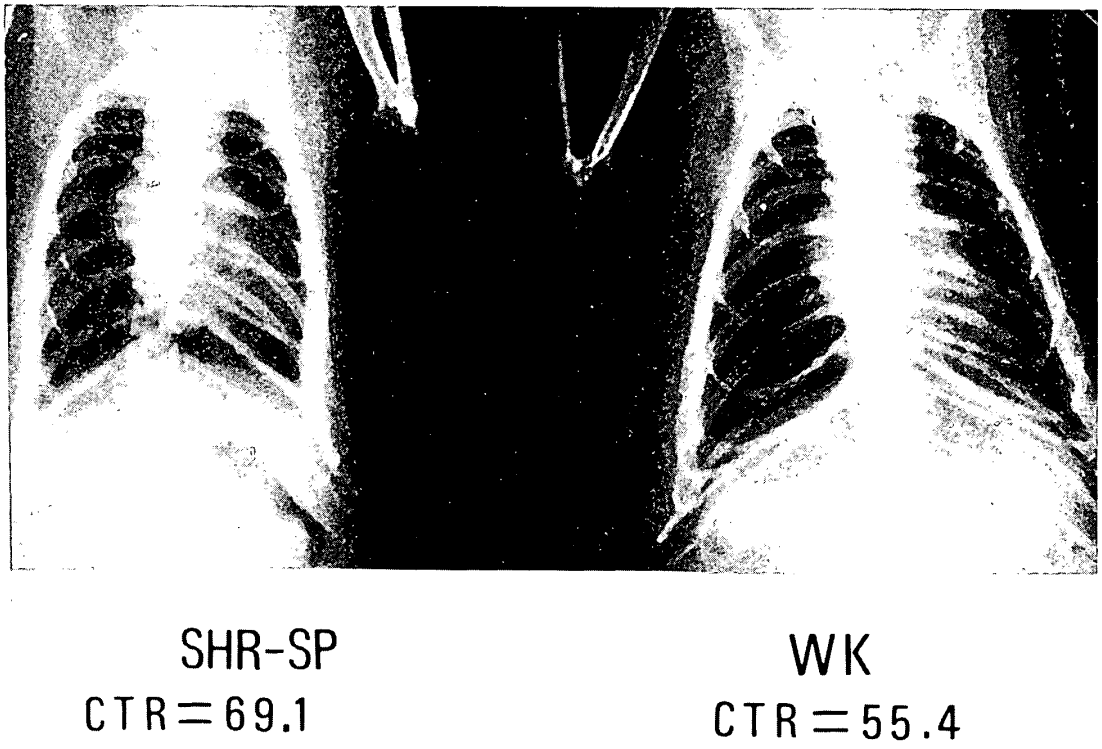

Fig.4. Chest X-ray photographs of WK and SHR. CTR: Cardiothoracic ratio (%).

SHRSP, had a tendency to become roundly swollen until arriving at the E point of VCG. This phenomenon was projected to the X scalar ECG as the depression of inversion of the ST-T wave and the prolongation of the QT interval. The averages of the QT intervals in WK and SHR were significantly different from each other, the values being 70.7 msec in WK and 106.8 msec in SHR (Table V).

Histometrical Findings

The weight and length (from the aortic ring to apex) of the heart, and the weight and thickness of the left ventricle (LV) and right ventricle (RV) were measured. Then the weight and length of the heart and the LV weight were divided by g body weight, and the ratio of LV weight to RV weight was calculated. The RV free wall was separated, the weight of which was defined as RV weight, and the interventricular septum was included in LV. The thickness of the interventricular septum and the free wall of LV was measured by slide calipers at the cross section in the middle of the long axis of the heart. The thickness of the free wall of LV was measured at three points – the anterior, posterior, and lateral walls of LV (Tables VI and VII).

SHR showed larger mean values than WK in all indices except RV thickness, where the means were almost the same. In SHR and WK, the ratios of the mean values of the LV wall thickness were almost the same, from the septum and the lateral wall of 1.3 to the posterior wall of 1.5.

TABLE X CARDIOTHORACIC RATIO OF 10-MONTH-OLD MALE SHRSP AND WK

Group	*No. of Animals*	*Cardiothoracic Ratio (%)*
WK	*4*	*53.1 ± 2.5*
SHR	*5*	*68.3 ± 1.7***

WK and SHR: Refer to Table I.
SHRSP: stroke-prone SHR
Values represent mean ± SE.
***: Statistically significant difference from WK ($p < 0.01$)*

Relationships among Vectrocardiogram, Histometrical Findings, and Blood Pressure

Blood pressure was closely correlated to the histometrical findings with significant correlative coefficiencies. For example, the heart weight was 0.903, the LV weight was 0.947, and the thick-

TABLE XI HISTOLOGICAL FINDINGS OF CORONARY ARTERIES AND MYOCARDIUM IN 4- AND 10-MONTH-OLD WK AND IN 5- AND 10-MONTH OLD SHR

Groups	No. of Animals	Arterial wall thickning			Perivascular fibrosis			Myocardial fibrosis		
		slight	moderate	severe	slight	moderate	severe	slight	moderate	severe
WK										
4-month-old	4	1	0	0	2	0	0	0	0	0
10-month-old	5	0	0	0	1	0	0	0	1	0
Total	9	1	0	0	3	0	0	0	1	0
SHR										
5-month-old	5	0	4	1	0	5	0	3	2	0
10-month-old	5	0	3	2	0	2	3	2	1	0
Total	10	0	7	3	0	7	3	5	3	0

WK and SHR: Refer to Table I. Values represent No. of animals.

ness of the lateral wall of LV was 0.902 (Tables VIII and IX).

Some of the vectrocardiographic findings were significantly correlated to blood pressure, and to most of the histometrical findings. The angle of the maximum QRS vector in the frontal plane, as well as that in the left sagittal plane, predominantly corresponded to the histometrical findings in such areas as the heart weight, the LV weight, the thickness of the anterior wall of LV. These negative correlative coefficiencies were −0.734, −0.779 and −0.825, respectively. Moreover, the magnitude of the maximum spatial QRS vector, QRS duration, time to maximum spatial QRS vector, and QT interval were also significantly correlated to the histometrical findings. However, the angle of the maximum QRS vector in the horizontal plane did not correspond to the histometrical findings, and in this experiment it was not able to be a good index for the left ventricular hypertrophy in SHR (Tables VIII and IX).

Findings of Chest X-Ray Photography

Cardiac enlargement was predominant in SHR, and the cardiothoracic ratio was significantly larger in SHR than in WK, the means being 53.1% in WK and 68.3% in SHR (Table X, Fig. 4).

Histological Findings

The abnormalities of coronary arteries and myocardium were examined microscopically in the rats of all experimental groups, 4- and 10-month- old WK, and 5- and 10-month-old SHR (Table XI, Fig. 5 and 6). Arterial wall thickening and perivascular fibrosis each in more than moderate grades were observed in none of WK and in all 10 SHR. These findings were severer in 10-month-old SHR than in 5-month-old SHR. Myocardial fibrosis being scattered in the myocardium was noticed in 8 of SHR and also in one of 10-month-old WK. These facts indicated that myocardial organic changes were much related to hypertension and that they were progressive particularly in SHR.

Discussion

Cardiac hypertrophy, especially left ventricular hypertrophy (LVH), was obviosly observed in SHR statistically as shown in Fig. 7. By means of chest roentgenography, this hypertrophy was also detected alive as cardiac enlargement, as shown in Fig. 4.

In SHR, LVH accompanied by spontaneous hypertension is a very important indicator for cardiac overload, which finally results in heart failure. It is also an important indicator of the process of cardiac fibrosis or myocardial infarction, which is observed under hypertensive state.

In order to detect these cardiac changes functionally or dynamically, in addition to electrocardiogram (ECG) we tried to apply vectrocardiogram (VCG) to rats. We chose the

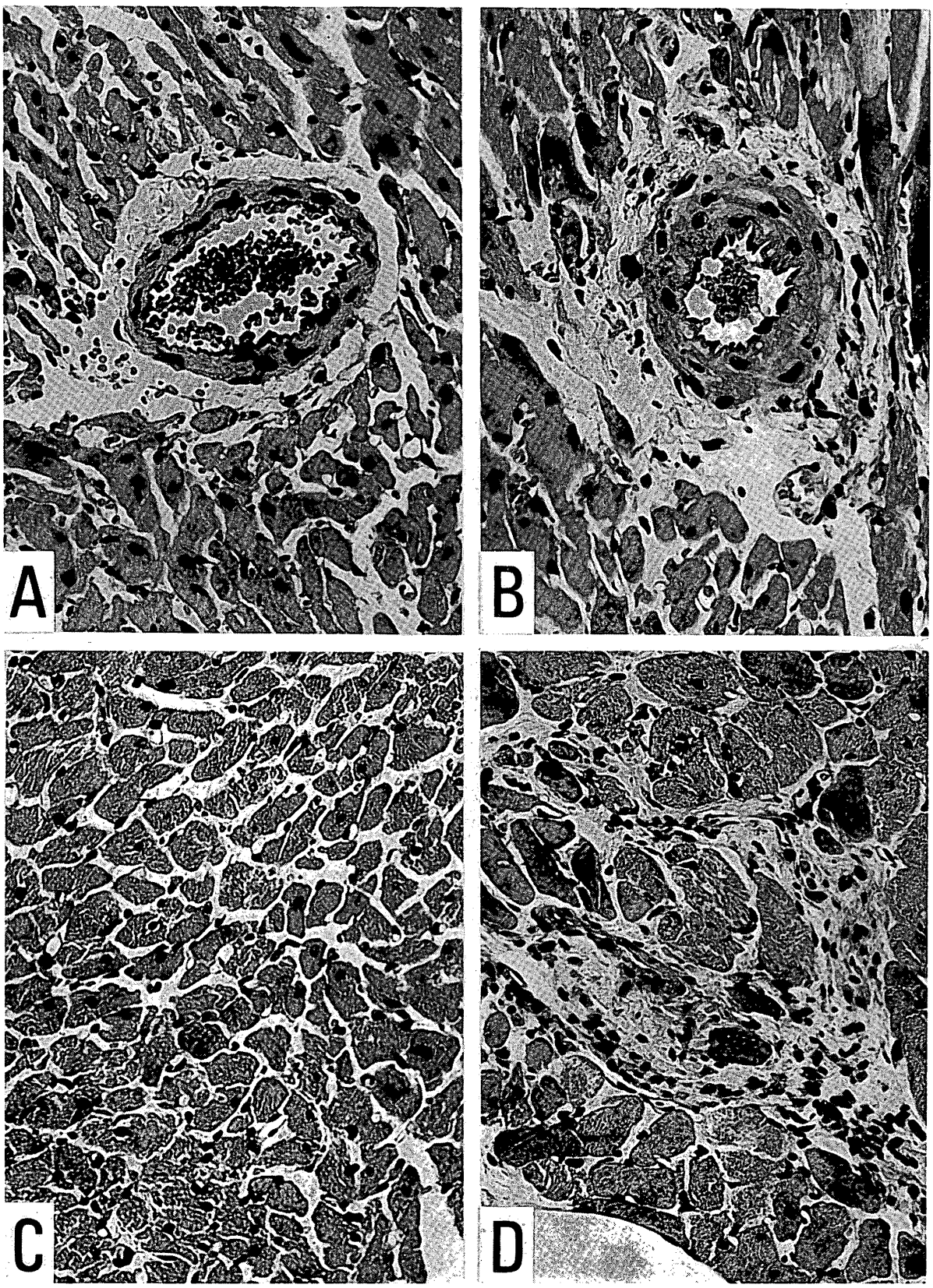

Fig.5. Histological findings of the coronary arteries and myocardium in the left ventricles: A and B: Coronary arteries in 4-month-old WK (A) and in 5-month-old SHR (B). C and D: Myocardium in 4-month-old WK (C), and in 5-month-old SHR (D). There are no particular pathological abnormalities in WK (A and C). However, in SHR (B and D) vascular wall thickening, perivascular fibrosis, intraluminal protrusion of the epithelial cells (B) and myocardial fibrosis in the papillary muscle (D). H.E. ×200.

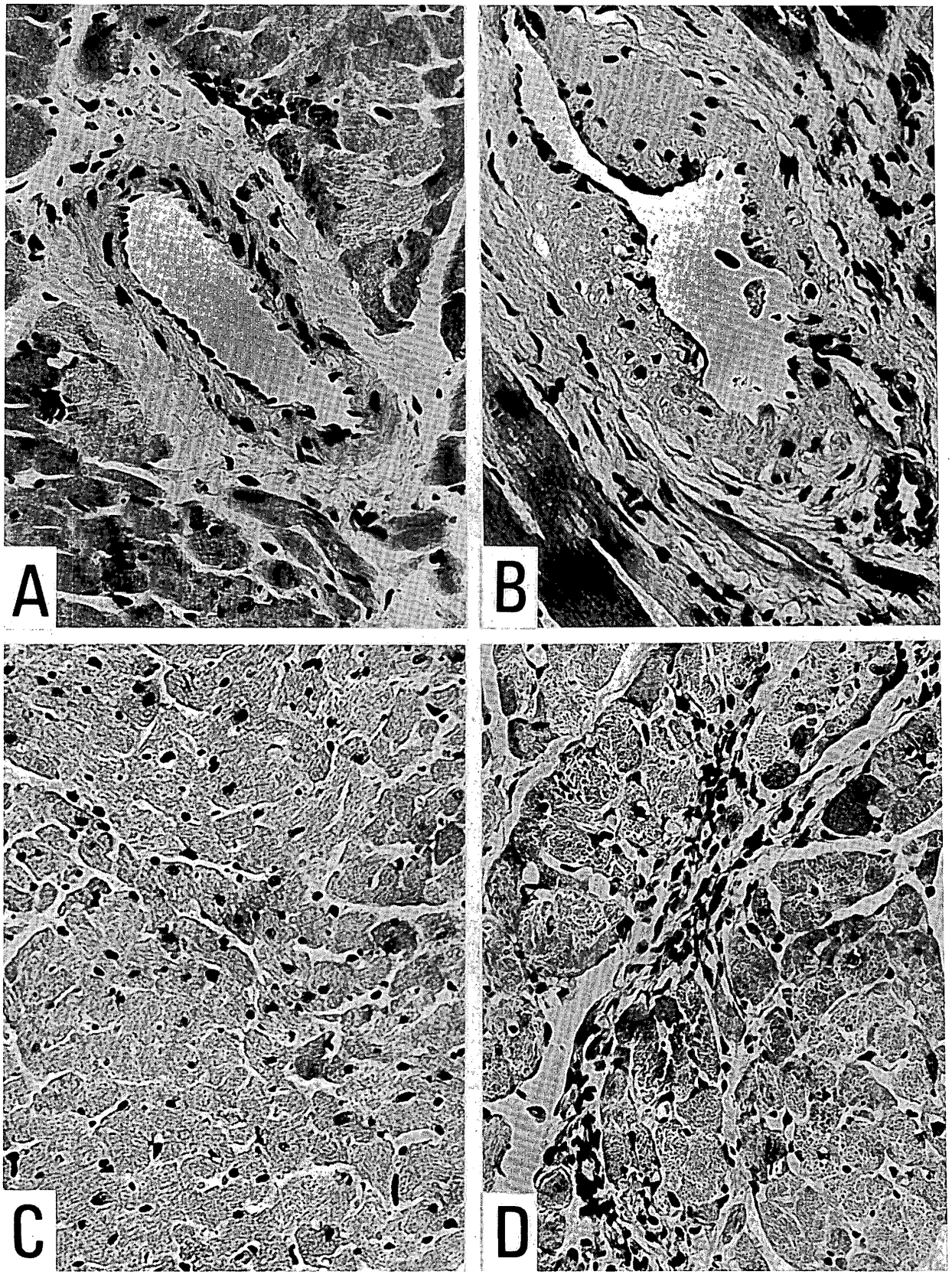

Fig.6. Histological findings of the coronary arteries and myocardium in the left ventricles: A and B: Coronary arteries in 10-month-old WK (A) and in 10-month-old SHR (B). C and D: Myocardium in 10-month-old WK (C), and in 10-month-old SHR (D). No particular pathological abnormalities are found in WK (A and C). On the other hand, in SHR (B and D), vascular wall thickening, perivascular fibrosis, intravascular proliferation (B) and myocardial fibrosis (D) are noticed. H.E. x200.

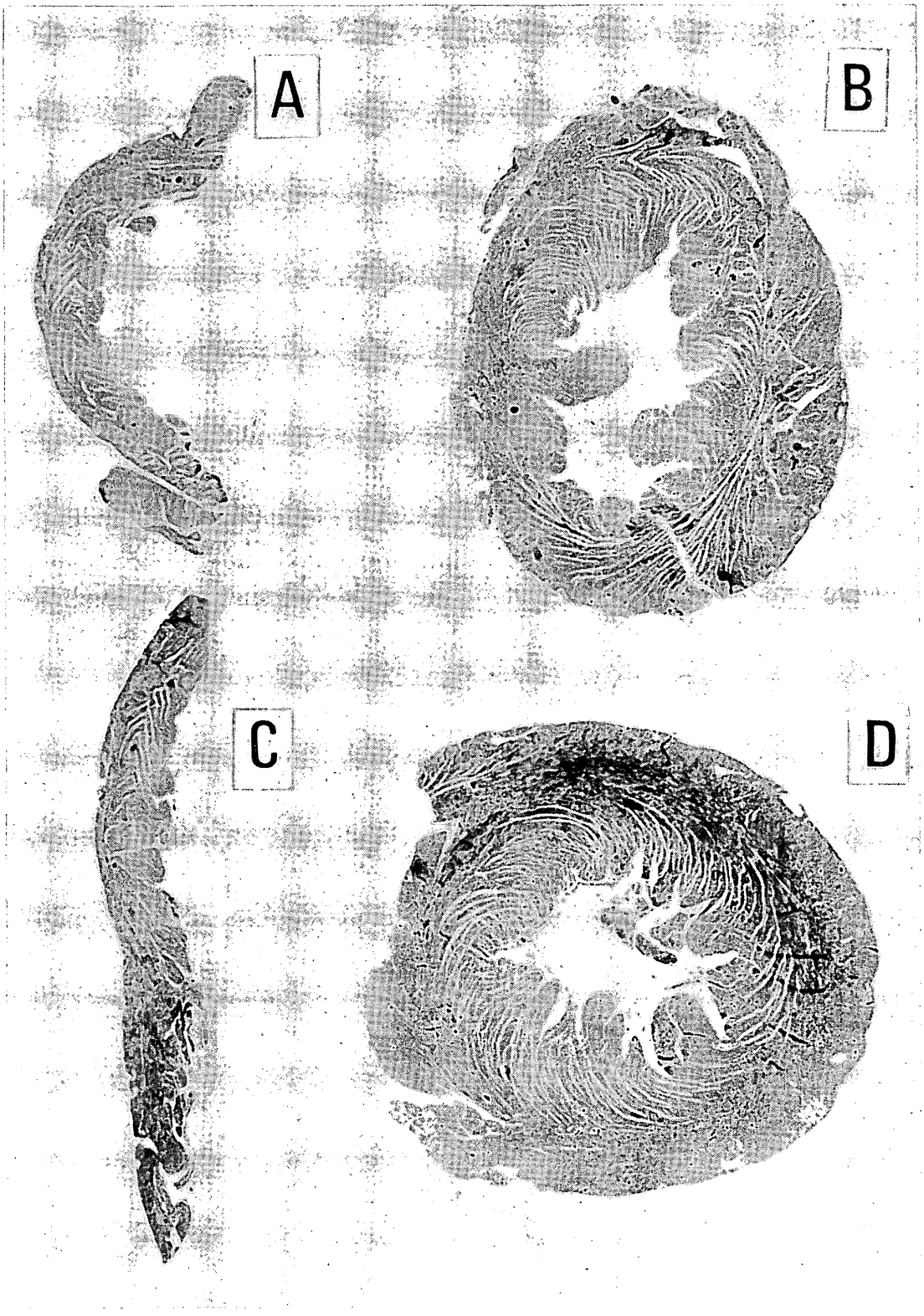

Fig.7. A and C show the right ventricular walls of WK (A) and SHR (C). B and D show the left ventricular walls of WK (B) and SHR (D). The thickness of the right ventricle is almost the same in WK and in SHR. The left ventricle is thicker in SHR.

Takayasu lead system as the most suitable VCG leads for small animals such as rats.

In this experiment, blood pressure was closely related to LVH. On the other hand, some of the vectrocardiographic findings – such as the angle of the maximum QRS vector in the frontal and

left sagittal planes, the magnitude of the maximum spatial QRS vector, QRS duration and so forth were significantly related to blood pressure and to histometrical findings such as heart weight, left ventricular weight, thickening of the left ventricular wall, and so forth. In SHR, the left axis deviation projected to the angles of the maximum QRS vector in the frontal and left sagittal planes may be the most conventional index of LVH. The QT interval was predominantly prolonged in SHR with ST-T changes. However, between the two groups, the angle of the maximum QRS vector in the horizontal plane was not significantly different.

Such vectrocardiographic findings in SHR at the same time presented characteristic features common to LVH in essential hypertension in humans.[16-18] Some of these features are as follows: Left axis deviation, increased magnitude of the maximum spatial QRS vector, prolongation of the depolarizing phase, ST-T changes and so forth. However, the left axis deviation may be more predominant in SHR than in essential hypertension in humans, while the angle of the maximum QRS vector in the horizontal plane does not tend to deviate to the left backward as in humans.

The prolongation of QRS duration and time to the maximum spatial QRS vector, with the increased magnitude of the spatial QRS vector, may be engendered primarily by the increased muscle mass – as already mentioned by *Uhley* and *Proctor*.[2] However, the repolarizing delay in SHR, observed as the prolongation of the QT interval with changes in ST-T, may be caused by an increase in the intact muscle mass itself, and also by a conduction disturbance due to such muscle degeneration as myocardial fibrotic changes (Fig. 5 and 6).

In other artificially-rendered hypertensive rats such as renal hypertensive or potassium-deficiencied rats,[1,2] the prolongation of QRS duration,[1] the tendency of a high R wave in the frontal plane,[2] the backward orientation of the spatial QRS vector in the horizontal plane,[1] and so forth are all reported as the electro- or vectrocardiographic findings in LVH. In some areas, the vectrocardiographic findings in SHR are different from those of these experimental hypertensive rats. For example, in SHR we see that the maximum QRS vector in the horizontal plane does not necessarily orient left backward, but rather we see an obvious left upward deviation of the maximum QRS vector in the frontal plane However, *Sambhi and White*[1] have reported a contrary observation.

It is interesting that LVH in SHR is more predominantly projected in VCG to the left upward deviation of the maximum QRS vector in the frontal plane than to the backward orientation in the horizontal plane. Whether this fact derives from the difference of species between rats and humans, or else from the difference of hypertension between spontaneous and other experimental hypertensions may be one of the questions still remaining.

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