External Graphic Methods and Simultaneous Catheterization Studies

HIDEO TAKEZAWA

THERE have been increasing amount of interest in the application of external graphic analysis to the studies of cardiovascular function since the last decade, chiefly for the purpose of evaluating left heart performance and the vascular response, in myocardial dysfunction status, such as in ischemic heart disease, cardiomyopathy and other similar clinical conditions. In considering left ventricular performance, it should be emphasized that the mechanical impedance matching between left ventricle, generator of periodic impulse and the arterial system, which exerts the visco-elastic properties, must be well balanced in order to keep maximal available power of "pumping out" stroke volume to "running off" into periphery (Fig. 1).

The purpose of this presentation is to analyse the finding obtained by external graphic studies including phonocardiography, apexcardiography and carotid as well as brachial arterial pulse wave, and to refer these to the data obtained by simultaneous right and left heart catheterization, including selective coronary arteriography and left ventriculography, in cases with arteriosclerotic heart disease, coronary heart disease, cardiomyopathy and other control group.

1) Left ventricular ejection time and preejection period:

In 33 cases, PEP and LV-ET were measured according to the methods described by Weissler and others,³⁻⁵ simultaneously during the time of right and left heart catheterization study, with left ventricular maximal dp/dt , isovolumetric

contraction time (ICT) and the cardiac output by direct Fick's principle and/or dye-dilution technics. Stroke volume was calculated by dividing cardiac output by heart rate. Cases consisted of 11 cases of arteriosclerotic heart disease (AHD), including 3 cases of coronary heart disease (IHD) demonstrated by selective coronary arteriography, 6 cases of cardiomyopathy (PMD) and 13 miscellaneous cases including 7 cases with rheumatic heart disease, 3 cases with atrial septal defect and 3 normal subjects.

As have been shown in the Fig. 2, the ratio of PEP/LV-ET did show highly significant negative correlation with stroke volume ($r=-0.839$). Deviation of PEP and LV-ET from normal value (Δ PEP and Δ LV-ET) based on Weissler's regression equation relating sex and heart rate,⁴ also showed negative and positive correlation with stroke volume, although more significantly in the former ($r=-0.784$ and $r=+0.690$, respectively). Correlations of PEP to isovolumetric contraction time (ICT) measured directly from the pressure tracing of the left ventricle and to the peak value of the first derivative of left ventricular pressure curve (LV max. dp/dt) were significant, as $r=+0.760$ and $r=-0.734$, respectively. These results are well in accordance with the previous observations and it appears to be justifiable to take PEP as close indices for ICT and LV max. dp/dt , which are also have been thought to be indicative of myocardial contractility.

2) Diastolic sound and atrial filling wave in myocardial disease:

It has been recognized, that in those circumstances such as in extensive coronary heart disease, cardiomyopathy or in other myocardial dysfunction, atrial gallop associated with abnormally augmented atrial wave (giant a-wave)

Key Words:

External Graphic Methods
LV Pressure Contour
Input Impedance for Arterial System

Professor of Medicine, Medical Clinic, Mie University Hospital, Tsu

* This paper was presented at the Symposium on "Hemodynamics in the Cardiovascular System" on the 36th Annual Meeting of the Japanese Circulation Society in Kanazawa, April 10, 1972.

Fig.1. Top: ρ represents internal resistance of electric power generator. Z represents circuit impedance, which should be equivalent to ρ to maintain maximal available power of the generator supplying to Z . When $\rho \neq Z$, electronic matrix should be interposed to equalize apparent output impedance to input impedance.

Middle: In the mechanical system, output impedance of the power generator, engine Z_1 is to be matched by changing angle velocity ω_1 through matching gear system to impedance Z_2 of the load, in order to supply maximal power from engine to the load.

Bottom: Grodins' electronic analog circuit¹ for the left heart is shown, in which ρ represents internal friction of myocardium, C_e represents elastic properties of myocardium, L represents inertia of stroke volume and R indicates resistance to flow in the outflow tract. Output impedance of LV is composed of these 4 parameters and is matched to input impedance for arterial system by the "Windkessel Funktion"² represented by C_{Ao} with Z . Increase in Z or decrease in C_{Ao} enhances increase in ρ or decrease in C_e , which can be interpreted practically as hypertrophy of myocardium, or vice versa.

in phono- and apexcardiography is one of the most common physical sign. Gorlin, Cohn and associates⁶ have reported recently that this sign

occurred in 75% of the cases with abnormal coronary arteriographic findings. In the Table, results of the polygraphic studies obtained here

Fig. 2. Relationship between PEP/LV-ET and stroke volume.

in 30 cases with AHD, including 12 cases with abnormal coronary arteriography, which shows more than 50% narrowing of at least one major coronary arterial branch, and 10 cases with cardiomyopathy are summarized. Although small in number, similar to Gorlin's incidence of graphic anomalies were recognized in coronary heart patients and in PMD group. Corresponding huge atrial contraction wave, so-called "atrial kick" was observed at the foot of ascending limb of left ventricular pressure curve, peak of the atrial kick exceeded 10 mmHg in all instances.

Fig. 3. For explanation, see text.

3) Pressure events in the left ventricle during ejection period:

Through series of observations on left ventricular pressure curve, I have become interested in the variation of pressure pattern presumed to be dependent on the magnitude of resistance to flow in the arterial circuit system. In the upper part of the Fig. 3, a mass, m is placed between coil spring, k and dashpot, r . The other ends of k and r are fixed as have been shown in the Figure. When displacement, x is applied to m , equation of movement becomes;

$$m \frac{d^2 x}{dt^2} + r \frac{dx}{dt} + kx = f(t)$$

Its electric analog is shown in the lower part of the Figure, in which inertia m , dashpot r and the coefficient of elasticity of spring k are represented as inductance L , resistance R and the reciprocal of the electric capacity C , respectively. The velocity of displacement x is represented as electric current i , and the force $f(t)$ is to be written as electric potential E . Thus the electric analog equation becomes as;

$$L \frac{di}{dt} + Ri + \frac{1}{C} \int i dt = E$$

TABLE I

	Number of cases	(%)
AHD with abnormal coronary arteriography	12	
Giant "a" with S_4	9	(75%)
Giant "a" with S_4 and S_3	5	(41%)
AHD with normal coronary arteriography	16	
Giant "a" with S_4	4	(22%)
Giant "a" with S_4 and S_3	0	(0%)
PMD	10	
Giant "a" with S_4	6	(60%)
Giant "a" with S_4 and S_3	3	(30%)

Fig.4. Modification of square wave of 1 c/s, by passing filter.

Top, indicates oscillatory case and lower presents a pattern of overdamping case.

which is famous as *Thomson's* equation, indicating transient phenomenon following immediately to the charge of L,C,R circuit as indicated in the Figure. When R is less than $2\sqrt{L/C}$, dumping is not enough to suppress oscillation, conversely, if R would be more than $2\sqrt{L/C}$, it exerts too much dumping that the circuit potential approaches to E with asymptotic fashion and never to cause oscillation. In the Fig.4, this phenomenon is shown by applying square wave with frequency of 1 c/s to L,C,R circuit, upper tracing is indicating oscillatory case with envelope of time constant $2L/R$, lower tracing is a logarithmically dumping case. These experimental observations appear to be the analog of left ventricular pressure curve during its ejection phase. Examples of LV pressure curve are shown in the Fig.5 obtained from 42 year-old normal female subject in the upper part, and from 50 year-old male subject with coronary arterial disease in

Fig.5. Left ventricular pressure tracings obtained from normal (top) and IHD cases (bottom). Examples for typical oscillatory and over-dumped pattern of the ejection phase.

anterior descending and circumflex branches in the lower part of the Figure. Former tracing indicates oscillatory pattern suggesting lower resistance to flow in the arterial system, while the latter shows non-oscillatory, over dumping case, in which following to an anacrotic shoulder, slow rising pressure with delay of its peak late in the ejection phase, indicating significant increase in output impedance of the left ventricle. In external graphic observations, commonly an ejection click followed by short decrescendo-type early systolic murmur synchronized to the anacrotic shoulder. These characteristic features of LV pressure were well correlated with clinical findings indicating increase in resistance to flow in arterial system.

4) Attempts to measure input impedance for the arterial system: Distortion of the arterial pulse contour as it travels down to periphery has been the subject of many concerns and debates

Fig.6. Left ventricular pressure pattern and distortion of arterial pulse contour as it travels down from central to periphery. Each numbers on the left side of tracings indicate the distance from the root of aorta in cm. Paper speed was changed in aorta (Ao) in the PMD case and in 5 cm position in the IHD case.

For further explanation, see text.

among the physiologists since *Otto Frank*⁷ first found in dogs some 70 years ago. We have been doing selective coronary arteriography since last 4 years, according to the way described by *Sones*.⁸ Before finishing up the whole procedure, we have made serial recordings of arterial pulse from the root of aorta to the right brachial artery on withdrawal by every 5 cm in 21 case. In the left side of Fig.6, LV pressure and serial tracings of arterial pulse on withdrawal from the root of aorta to brachial artery in 45 year-old female cardiomyopathy case with completely normal coronary arteriographic findings are shown. LV pressure curve indicates "atrial kick" at the foot of ascending limb of LV pressure and ejection pattern presents typical oscillatory case, suggesting normal resistance to flow in the arterial system. The marked distortion of arterial pulse contour from aorta to brachial artery is noted. As

the pulse travels down, anacrotic wave became prominently peaked, exceeding aortic systolic pressure by more than 10 mmHg, tidal wave became attenuated and dicrotic wave steeper. It seems likely to be in accordance with the opinions of *Warner*,⁹ *Peterson*¹⁰ and many other investigators¹¹⁻¹³ that this distortion of pulse wave is based on summation effects of resonance and band pass filtering mechanism exerted by visco-elastic properties of arterial system. On the other hand, in sclerotic case such as shown in the right side of the Fig.6, with variant form angina and wide spread coronary arterial obstructive change, hemodynamic feature behaves in different ways. LV pressure exhibits over dumping type ejection pattern and the distortion effects of arterial pulse contour from aorta to brachial artery is almost absent, which suggests change of visco-elastic properties of the arterial wall into

Fig.7. Circuit diagram of the filter amplifier.
For explanation, see text.

Fig.8. Synthesis of brachial arterial pulse through filtering central aortic pressure pulse. Left tracing was obtained from 27 year-old female, with mitral stenosis, and in the upper part, central aortic pulse (top), it's modification, i.e., synthesis of brachial pulse (middle) and EKG (bottom). In the lower part, original brachial pressure pulse and EKG are shown. Right tracing was obtained from 65 year-old male with 60% narrowing in the root of anterior descending coronary artery by angiogram and clinical picture of angina on effort. Tracings are shown in the same order as in left side.

Fig.9. Relationship between % mean distensibility of ascending aorta and modulus and phase angle of the input impedance for arterial system. Black circles and black triangles represent cases with normal and abnormal coronary arteriogram, respectively. Modulus is presented as a value for 5 c/s. Phase angle is obtained as a half of total shift of the angle from 1 to 20 c/s.

Fig.10. Diagram of the methods for estimation of input impedance for arterial system. Original carotid pulse and its modification are visualized with simultaneous brachial pulse contour on the oscilloscope.

more rigid character. Resonance frequency shifted to much higher side, pressure contour in the central aorta was transmitted to periphery

without getting distorting effects as though traveling through solid pipe. This finding was especially impressive in its parallelism with the

Fig.11. Simultaneous recordings of externally obtained carotid arterial pulse contour and brachial arterial pulse. Upper part and lower part indicate recordings from 44 year old normal male and 65 year old male with angina of effort. Each tracings are from top to below; original carotid pulse, it's modification through filter-amplifier, brachial pulse and EKG.

severity of coronary disease. Atherosclerotic damage to aortic arch leads to impairment of "Windkessel Funktion". Thus created "water hammer" in the root of aorta is presumed to be playing an important role in the pathogenesis of coronary heart disease, by pounding main branchings of coronary arteries.

In an attempt to estimate the input impedance for arterial system, electric analog circuit was constructed as indicated in the figure 7, which is identical in the circuit composition to the unit segment of electric analog of the entire arterial system described by *Noordergraaf*,¹⁴ and *Beneken*.¹⁵ The central aortic pressure was passed through this filter box and it's output was amplified and visualized on cathod-ray oscilloscope. L,R,C and r' were adjusted separately so as to make filtered aortic pressure similar to brachial pressure contour as close as possible.

Two examples of this analysis are shown in the Fig.8. The input impedance of filter circuit thus obtained was calculated. In 8 case, including 4 cases of IHD, left ventriculography was also performed and the distensibility of the ascending aorta was calculated according to the way described by *Yaginuma*.¹⁶ Modulus, Z was presented as a value at 5 c/s and it's phase angle was expressed as a half of the total shift in degree from 1 c/s to 20 c/s. In the Fig.9, mean % distensibility of the ascending aorta was plotted on ordinate against modulus and phase angle of input impedance for arterial system on abscissa, which show significant relationship between distensibility of aorta and functions of input impedance for arterial system. It is also evident that IHD group indicates significantly reduced distensibility of aorta and increase in modulus, decrease in shift of phase angle of the input impedance.

Another attempt was made, in which input impedance for the arterial system was sought by external graphic method. Carotid arterial pulse was simulated as central aortic pulse and the same type of analysis as above was made with simultaneously recorded brachial pulse. Procedure is illustrated in the Fig.10. The output of carotid arterial pulse from the 4-channel data recorder was divided into two, one is visualized directly on the oscillograph and the other one fed to the above mentioned filter-amplifier, through which it was visualized on the scope. The carotid arterial pulse was modified by adjusting the filter box and made similar to brachial arterial pulse as closely as possible. In the Fig.11, examples of normal and IHD cases are shown. Each photographs indicating from top to below, carotid arterial pulse, it's modification by filter box, brachial pulse and EKG. In the next Fig.12, transference function of the filter box is shown. Sine wave signal of constant magnitude was given continuously from 1 to 20 c/s by each one c/s and 25, 30 and/or 40 c/s, the output from filter box was recorded. In the normal subjects, significant decline of impedance between 2 and 10 c/s is impressive, while in IHD case, almost flat response to frequency change may be noted. In each cases, upper and lower picture indicate, filter characteristic obtained by direct intra-arterial catheterization technic and external graphic method, respectively. Similarity of the results obtained by two different technic will be noted. Finally calculated modulus and phase angle in mega ohm and degree are shown

Fig.12. Frequency response of the filter box obtained from normal (left side) and IHD case (right side). On each side, upper part indicates data from intra-arterial catheterization, while in lower part, data obtained by external graphic methods are shown. Further explanation in the text.

Fig.13. Modulus and phase angle of the input impedance for arterial system. Left and right side are data obtained from normal and IHD cases, respectively. Data are plotted against frequency in c/s.

on the left and right ordinate against frequency from 1 to 20 c/s on the abscissa, in the Fig.13. Normal case on the left side indicates lower modulus and higher frequency response, while IHD case on the right hand shows increase in modulus and poor frequency response. One word should be added that the external pulse recording must be performed under care to avoid distortion of pulse wave by improper application of pick-up, in this kind of study, requiring frequency analysis.

SUMMARY AND CONCLUSION

Evaluations of external graphic studies were made in comparison with left and right heart catheterization data, including selective coronary arteriography and left ventriculography.

1) PEP and LV-ET and the ratio of PEP to LV-ET were verified as significant indices for LV maximal dp/dt, LV isovolumetric contraction time and stroke volume.

2) In myocard dysfunction syndrome such as IHD or in PMD, significantly higher incidence of graphic anomaly including giant a-wave in apex-cardiogram with atrial sound and/or third sound was observed.

3) LV pressure curve during ejection phase in normal subjects showed oscillatory dome-shaped pattern, while in sclerotic subjects, LV pressure did show slow-rising over-dumped pattern.

4) Pulse wave contour distortion as traveling down from central aorta to brachial artery was analysed utilizing L,C,R analog filter net work, and the input impedance for arterial system was calculated. In sclerotic subjects, especially in IHD cases, modulus was significantly higher and the shift of phase angle was definitely less as compared to non-sclerotic subjects. Distensibility of ascending aorta was less in IHD cases and correlated well with the change of impedance.

5) Another attempt was also made to measure input impedance for arterial system by external graphic methods, including carotid arterial pulse and brachial pulse wave, utilizing the same procedure of L,C,R filter net work. Satisfactory parallelism between results obtained by intra-arterial catheterization and external graphic methods was appreciated, provided, appropriate care to avoid artifact or distortion in arterial pulse wave was made.

REFERENCES

1. GRODINS, F. S. & BUONCRISTIANI, J. F.: In *Physical Basis of Circulatory Transport* (E. B. Reeve & A. C. Guyton: Editors) Philadelphia, W. B. Saunders, Co., 1967, p.61.
2. FRANK, Otto.: *Zeitschr. fur Biol.* 32: 370, 1895.
3. WEISSLER, A. M., PEELER, R. G., & ROEHILL, W. H.: *Am. Heart J.* 62: 367, 1961.
4. WEISSLER, A. M., HARRIS, W. S., & SCHOENFELD, C. D.: *Circulation* 37: 149, 1968.
5. WEISSLER, A. M., HARRIS, W. S., & SCHOENFELD, C. D.: *Am. J. Cardiol.* 23: 577, 1969.
6. COHN, P. F., VOKONAS, P. S., WILLIAMS, R. A., HERMAN, M. V., & GORLIN, R.: *Circulation* 44: 196, 1971.
7. FRANK, O.: *Ztsche. Biol.* 46: 441, 1905.
8. SONES, F. M. & SHIREY, E. K.: *Modern Concepts Cardiovasc. Dis.* 31: 735, 1962.
9. WARNER, H. H.: *Am. J. Physiol.* 183: 670, 1955.
10. WARNER, H. R.: *Circulation Res.* 5: 79, 1957.
11. PETERSON, L. H. & GERST, P. H.: *Fed. Proc.* 51: 144, 1956.
12. REMINGTON, J. W. & WOOD, E. M.: *Am. J. Physiol.* 183: 654, 1955.
13. KROCKER, E. J. & WOOD, E. M.: *Circulation Res.* 3: 623, 1955.
14. NOORDERGRAAF, A., VERDOUW, P. D., & BOOM, H. B. K.: *Prog. Cardiovasc. Dis.* 5: 419, 1963.
15. BENECKEN, J. E. W. & DEWIT, B.: In *Physical Basis of Circulatory Transport* (Reeve, E. B. & Guyton, A. C.: Editors) Philadelphia, W. B. Saunders, Co., 1967, p.1.
16. YAGINUMA, T. & WAKABAYASHI, A.: *Jap. Circul. J.* 33: 1541, 1969.