Motoharu Hasegawa: A Fundamental Study on Human Aortic Pulse Wave Velocity. Tokyo Jikkei Medical College Journal, 1970; 85:742-760

Translated by

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I. Introduction

Moens reported the results of the experiment on pulse wave velocity (PWV) using artificial blood vessels in 1872[1]. Since then a number of studies have been published on this topic, but none of them have successfully elucidated the mechanism of pulse wave transmission and established the significance of the measurement of PWV in situ.

In 1922, experimental findings by Bramwell, Hill and others[4-7] showed that the pulse wave velocity was dependent on the modulus of volume elasticity. Most studies of PWV thereafter have been theoretically based on Bramwell's findings, without the development of new theories, and recent studies have placed their major focus on the measurement of elasticity of isolated blood vessels[27-38]. The reasons for the stagnation of progress in studies of pulse wave velocity are summarized as follows:

1. Enough progress has not been made in the theoretical interpretation of the initiation and transmission mechanism of pulse waves in situ, especially the analysis of circulatory and vascular factors which influence PWV.

2. The properties of vascular elasticity under the dynamic condition of blood circulation had been viewed from the standpoint of static elasticity rather than being viewed from the standpoint of dynamic viscoelasticity.

3. It was impossible to conduct experiments on PWV by using isolated human blood vessels in the past.

Furthermore, technical difficulties were involved in recording wave patterns to measure PWV.

Accordingly, the present study is to elucidate the essential properties and mechanisms of pulse wave transmission by overcoming the above obstacles. Basic experiments were performed using 65 excised human aortas under the same dynamic circulatory conditions as those in a living subject. The author discusses the following PWV issues:

1. Analysis of the circulatory factors (stroke volume, pulse rate, blood viscosity and minimum internal pressure);
2. Analysis of vascular factors under constant or varying minimum pressure (diameter, mural thickness, external diameter/internal diameter ratio, Young's modulus of the arterial wall)
3. Comparison of antemortem PWVs with postmortem PWV's
4. Preparation of the nomogram table for PWV standardized for diastolic blood pressure.

II. Circulatory Factors Affecting PWV

1. Materials and Methods

1) Sample A (Table 1)

This sample is comprised of the aortas excised from 22 patients, consisting of 16 males and 6 females, between 18 and 89 years of age, who died of malignant tumors, cerebral vascular damage, renal and hepatic failure, etc., and were autopsied within four hours after death.

Table 1. The materials for analysing the circulatory factors

No.	Sex	Age	Diagnosis	PWV*
1	M	35	Malig. hypertension	5.7
2	M	18	Cerebral injury	6.2
3	M	35	Chronic nephritis	7.2
4	M	45	Gastric ulcer	7.8
5	M	53	Cirrhosis of liver	8.0
6	M	80	Cirrhosis of liver	8.3
7	M	40	Cirrhosis of liver	8.5
8	F	63	Cancer of bile duct	8.7
9	M	29	Neuroepithelioma	8.8
10	F	59	Nephrosclerosis	9.1
11	M	68	Cancer of lung	9.5
12	F	55	Biliary stones	9.8
13	F	56	Cancer of lung	9.9
14	M	70	Leukemia	10.0
15	M	60	Cancer of bile duct	10.4
16	M	72	A. R.	10.7
17	M	73	Cerebral bleeding	11.0
18	M	65	Cerebral bleeding	11.9
19	M	89	Cancer of prostate	12.7
20	M	65	Cancer of pancreas	13.7
21	F	74	Pneumonia	14.1
22	F	52	Cancer of ovary	18.7

* Pulse wave velocity (m/sec) : normalized value at diastolic press. of 80mmHg.

2) Methods

(1) The Apparatus (Fig. 1)

The apparatus is comprised of two systems:

a) Circulation System

The artificial circulation system was comprised of (a) Davol's auxiliary circulator (derived by compressed air the experimenter can control the pulse rate, circulation rate, duration of systolic phase and of the diastolic phase), (b) a pressure buffer (a crude rubber ball, acting as the pressure buffer for peripheral resistance), (c) peripheral resistance control valve (equipped with a cock for fine adjustment of peripheral resistance), and (d) perfusing tube (a rubber tube of 15mm in internal diameter for connecting one apparatus to another).

In the above-mentioned circulation system, the isolated aorta were inserted between the Davol's pump and the pressure buffer. The aorta to be inserted had been preserved in an airtight vinyl bag at 4 C. from autopsy until the start of the experiment; and it was stripped of the circumferential tissues, and of the ramified arteries from the aorta immediately before insertion.

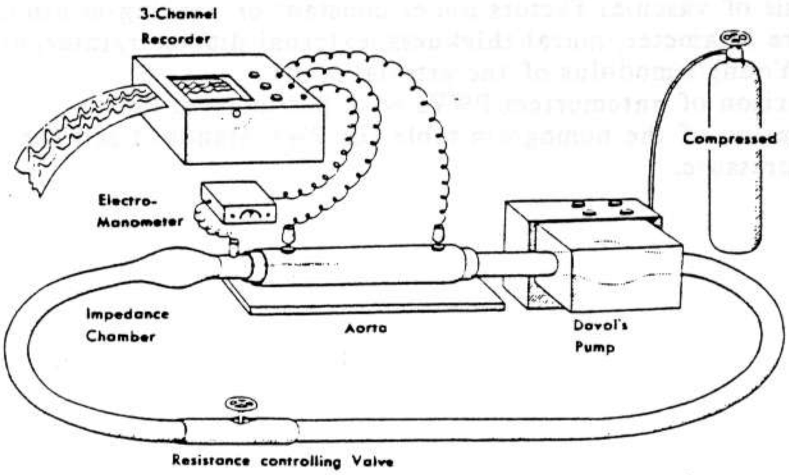


Fig. 1. Blockdiagram of measuring pulse wave velocity for isolated aorta

b. Measuring and Recording Systems

The measuring system is comprised of two sets of direct type pulse wave pickup microphones attached to the central and peripheral stumps of the outer coat of the isolated aorta so inserted and immobilized to the circulation system and the amplifiers thereof, and the manometric steel needle inserted into the peripheral stump of the aorta. The recording system has a three element recorder capable of synchronously recording two channels of pulse wave patterns and one channel of pressure wave patterns.

(2) Items Examined

In order to examine the circulatory factors associated with PWV, the following four factors were analyzed under given conditions. Of the internal pressure factors, the minimum internal pressure was taken up because of the method for discerning the time lag in terms of wave patterns (see VII-2 under Discussion).

a) Internal Pressure (minimum internal pressure)

Each of the 22 aortas was inserted into the artificial circulator to examine the effect of the minimum internal pressure. The Davol's pump was adjusted to the stroke volume of 60 ml and a pulse rate of 60 beats per minute. The effect of variations in internal pressure on PWV in the perfusing solution with a viscosity of 5 centipoise and 60 shear rate (cm^{-1}) were examined by changing the minimum internal pressure by each 10 mmHg in the range of 40 to 130 mmHg by the use of the peripheral resistance controlling valve. Then, variation in PWV corresponding to changes in the internal pressure are examined under each of the following conditions, (2) and (3).

b) Stroke Volume

By using the aorta of Case 2, the effect of variations in the minimum internal pressure on PWV were examined under three different stroke volumes, namely, 40, 50, and 60 ml., with the pulsation rate adjusted to 60 beats per minute and the perfusing solution with a viscosity of 5 centipoise and 60 shear rate (cm^{-1}).

c) Minute Pulse Rate

For case 14 the effects of variation in the minimum internal pressure on PWV were examined under three different minute pulse rates, namely, 40,60, and 90 beats per minute, with the stroke volume adjusted to 60 ml., and the perfusing solution with a viscosity of 5 centipoise and 60 shear rates (cm^{-1}).

d) Viscosity of the Perfusing Solution

By using the aorta of case 21, the effects of variation in the internal pressure on PWV were examined under two different types of viscosities of the perfusing solution, namely, 5 centipoise and 60 shear rate (cm^{-1}), and 3 centipoise and 60 shear rate (cm^{-1}), with the stroke volume of 60 ml., and the pulse rate of 60 beats per minute. The perfusing solution used was the isotonic saline solution containing a low-molecular dextran power. The solution with viscosity of 5 centipoise is isoviscous to blood, and that with viscosity of 3 centipoise is hypoviscous to blood.

(3) Recording

After each of the isolated human aorta was inserted into the artificial circulator, two channels of pulse wave and one channel of pressure waves were synchronously recorded in the sequence of conditions a), b), c) and d) in item (2), on the three element recorder with a roll of paper running at a speed of 100 mm/sec.

(4) Method for Measurement of Artificial Pulse Wave Velocity.

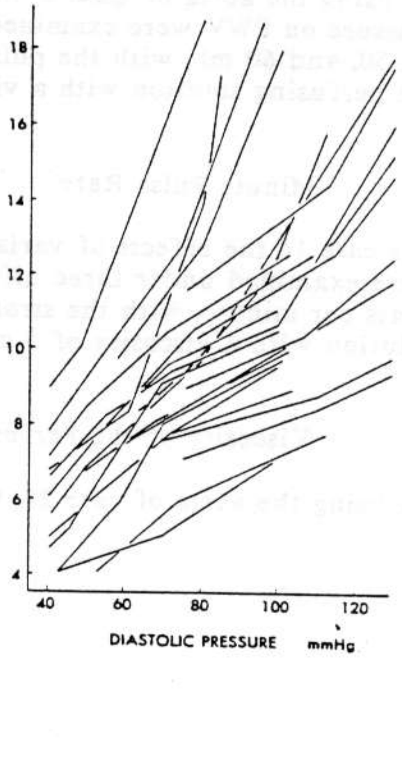
Of the three wave patterns recorded, the time lag, t, between the uprise of pulse wave on the central stump and that of the peripheral stump is measured, and the pulse wave velocity, C, calculated from the distance, D, between the two points on the artery where the pulse waves are recorded may be given as D/t m/sec. The minimum internal pressure was measured by means of the synchronously recorded pressure wave patterns and the pressure nomographic curve prepared beforehand. Based on these findings, the minimum internal pressure PWV curve was developed.

2. Results

Effects of the circulatory factors on PWV were examined: (1) internal pressure (22 cases), (2) stroke volume (Case 2), (3) pulse rate per minute (Case 14 and 4) viscosity of perfusing solution (Case 21). The following results were found:

1) Minimum Internal Pressure

Figure 2 shows the relationship between PWV and minimum internal pressure, based on the observation of 22 aortas. The curves indicate that PWV had positive correlation with minimum internal pressure; PWV increased as the internal pressure rises with some individual differences. In other words, as the internal pressure gives a rise, the rate of an increase in PWV becomes greater. The curves in Fig. 2 show an upwardly convex pattern at the portion below 8.2 m/sec of PWV, almost linear shape 8.3 and 9.7 m/sec, and an inverted convex pattern in the part greater than 9.8 m/sec.



2) Stroke volume

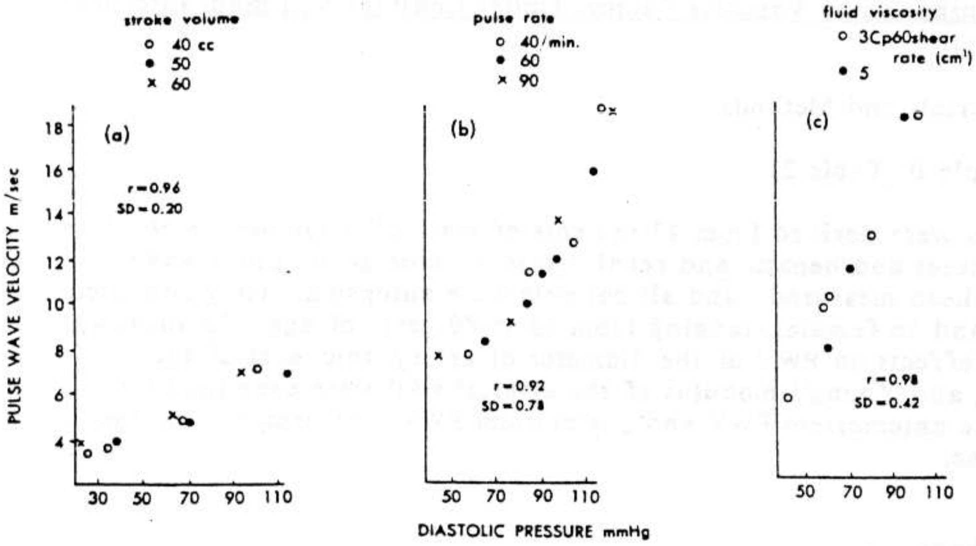


Fig. 3

Relation between PWV and circulatory factors

Presented in Figure 3-a is the relationship between PWV and the minimum internal pressure under three different conditions of stroke volume, namely, 40 ml. (marked o), 50 ml. (marked ●) and 60 ml. (marked x). Their correlation coefficient (*r*) was 0.96, and the standard deviation, 0.20.

3) Minute pulse rate

Shown in Figure 3-b is the relationship between PWV and the minimum internal pressure under three different conditions of minute pulse rate, namely, 40 beats (marked o), 50 (marked ●) and 90 (marked x). Their correlation coefficient was 0.92, and standard deviation, 0.78.

4) Viscosity of perfusing solution

Given in Figure 3-c is the relationship between PWV and the minimum internal pressure under two different viscosities of the perfusing solution, namely, 3 centipoise with 60 shear rate (cm^{-1}) (marked o) and 5 centipoise with 60 shear rate (cm^{-1}) (marked ●). Their correlation coefficient (*r*) was 0.98, and the standard deviation, 0.42.

3. Summary

1) The effects on PWV of stroke volume, minute pulse rate and viscosity of perfusing solution proved so small that they were negligible under various physiological conditions.

2) Among the circulatory factors under the throbbing flow, PWV proved to be most influenced by the minimum internal pressure. PWV increases as the minimum internal pressure rises. The higher the pulse wave velocity, the steeper the slope of PWV-minimum internal pressure curve.

III. Examination of Vascular Factors Under Constant Minimum Internal Pressure

1. Materials and Methods

1) Sample B (Table 2)

The materials were derived from 43 patients of malignant tumors, cerebral and coronary diseases and hepatic and renal diseases whose aortic pulse wave velocity had been measured, and all patients were autopsied. They consisted of 27 males and 16 females, ranging from 13 to 80 years of age. On these 43 patients, the effects on PWV of the diameter of artery, thickness of the arterial wall, and Young's modulus of the arterial wall were examined by measuring the antemortem PWV and postmortem PWV measurements of the isolated aortae.

2) Methods

(1) Method for the measurement of aortic PWV in situ

Because this method is described in detail in the paper by Hayashi et al.[39], it is briefly outlined below:

a) Recording Method (Figure 4)

The Fukuda Schwarzer Physiopolygraph Model ST-4, which was used as a PWV measurement device, was capable of synchronously recording electrocardiogram, cardiac sound and two channels of pulse wave patterns. For recording, the subject is first laid in the supine position; the cardiac sound pickup microphone is placed on the chest wall. Then, pulse wave pickup microphones are attached to the throbbing parts of both carotid and femoral arteries. Recognizing the precomponents of cardiac II sound, uprise of two pulse waves and the scar on the carotid artery let the subject hold their breath slightly, and synchronous recording is made during 5 to 6 heart beats. Immediately after the recording, the blood pressure at the right brachial artery is measured.

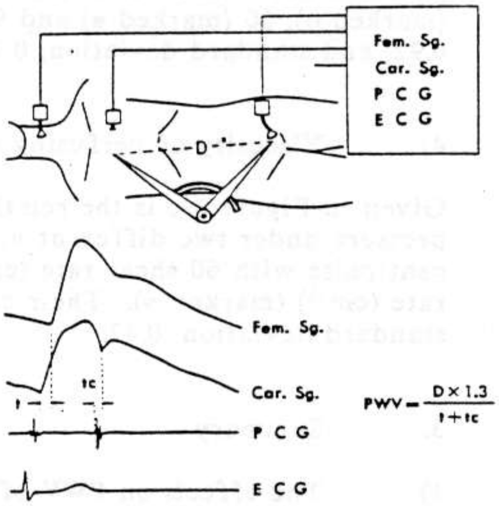


Fig. 4. Method of registration and calculation of pulse wave velocity of aorta

b) Methods for Measurement and Calculation

The time lag between the uprise of the carotid artery pulse wave and that of

Table 2. The materials for analysing the wall factors

No.	Sex	Age	Diagnosis	Diameter (mm)	Thickness (μ)	PWV m/eec
1	M	34	Chronic nephritis	50.60	1364	7.4
2	F	36	Chronic nephritis	61.66	1122	8.1
3	M	51	Cirrhosis of liver	48.20	1170	8.0
4	M	48	Heart failure	66.00	1362	9.6
5	M	51	Cirrhosis of liver	52.40	1394	7.1
6	F	53	Chronic nephritis	53.00	1354	9.5
7	M	53	Cancer of stomach	51.60	1582	7.7
8	F	50	Liver atrophy	44.60	1282	7.5
9	M	73	Cancer of lung	52.00	1518	11.4
10	M	35	Chronic nephritis	49.75	1546	7.7
11	F	74	Cancer of lung	61.60	1248	12.4
12	M	72	Heart failure	74.00	1158	10.0
13	F	56	Chronic nephritis	56.60	1256	11.4
14	F	55	Cholelithiasis	55.00	1606	10.1
15	F	53	Cancer of lung	58.00	1440	10.6
16	M	29	Chronic nephritis	44.00	1468	8.1
17	F	62	Myocardial infarction	45.33	1364	15.2
18	F	62	Cerebral injury	52.33	1202	9.4
19	F	31	Cancer of stomach	41.60	1028	6.8
20	M	61	Leukemia	44.80	1634	7.7
21	M	52	Chronic nephritis	—	1178	6.3
22	M	35	Malig. hypertension	55.40	1544	6.2
23	F	56	Cirrhosis of liver	48.40	1372	9.2
24	F	27	Peritonitis carcinomatosa	44.50	1156	5.3
25	M	64	Cirrhosis of liver	50.75	1300	7.5
26	F	58	Cancer of liver	49.80	1196	7.4
27	M	52	Cirrhosis of liver	47.00	1402	9.5
28	M	57	Mediastinal tumor	57.40	1562	7.2
29	M	38	Cancer of liver	55.20	1466	7.4
30	M	80	Cancer of stomach	59.40	1256	13.2
31	M	50	Myocardial disease	48.00	1458	7.2
32	F	65	Cancer of bladder	49.00	1496	8.0
33	F	76	Cancer of bladder	49.80	1506	8.5
34	M	13	A.S.D. and A.I.	44.60	900	7.5
35	M	64	Cancer of lung	61.00	1448	9.8
36	M	33	Cirrhosis of liver	43.20	788	7.9
37	M	55	Gastric ulcer	64.00	1284	8.9
38	F	23	Leukemia	39.75	976	6.8
39	M	68	Cancer of lung	57.75	1540	8.4
40	M	73	Pritonitis carcinomatosa	64.00	1488	12.2
41	M	38	Cancer of stomach	51.40	1946	8.5
42	M	64	Myocardial infarction	62.80	1510	10.3
43	M	26	Cancer of lung	40.80	1200	7.0

PWV (Pulse Wave Velocity (m/sec)) : normalized value at diastolic Press. of 80mmHg the femoral arterial pulse wave is measured as t. The time lag between the precomponent of the cardiac II sound and the scar of the carotid artery is measured as t_c. The actual length of the measuring portion of the aorta was obtained by multiplying the straight distance, D, between the second intercostal region of the right margin of the sternum and throbbing part of the femoral artery by the anatomical modification value, 1.3[25]. The aortic pulse wave velocity (PWV), C, is expressed as:

$$C = [\ (D \times 1.3) \ / \ (t + t_c)\ ]_p$$

where *p* is the minimum internal pressure or diastolic blood pressure in the right brachial arterial immediately after measurement of PWV.

(2) Examination of the Isolated Aortas

Based on the aortas isolated from the 43 patients (listed in Table 2) whose antemortem aortic PWV was available, the following examinations were made.

a) Diameter (Mean Diameter)

The aorta was vertically incised from the ostium to the part where the common iliac artery bifurcates in order to measure the incised widths of (a) the ostium, (b) the arch, (c) the part where the fifth posterior intercostal artery bifurcates, (d) the part where renal arteries bifurcate, (e) the part immediately above the bifurcation of the common iliac artery. Then, the mean radius of the five parts (a-e) was calculated.

b) Thickness of the aorta wall (inner coat and middle coat)

Tissue specimens were collected from the flat part of the inner coat surface at the above-mentioned five parts of the aorta, and after staining by Elastica van Gieson method, the thickness of the inner coat and that of the middle coat were measured with micrometer, and the mean thickness of the wall at the five places (a-e) was defined as the mural thickness.

3) Items Examined (Table 3)

Based on the measured data on Materials B (43 patients), correlation coefficients were obtained between PWV and (a) diameter of the aorta, (b) thickness of the aortic wall and (c) Young's modulus of the aortic wall. Procedures are explained as follows. On materials B, the antemortem PWV were measured by the aforementioned methods (see VI-2 Results); PWV at the minimum internal (or diastolic pressure) of 80 mmHg according to the pressure monographic curve. The viscosity coefficient of blood is assumed negligible here, and if the minimum internal pressure is assumed constant, PWV (C) may be presented as Moens-Korteweg's formula,

$$C = Eh/(1 - \sigma^2)\rho D \quad (1)$$

Formula (1) gives E as $E = (1 - \sigma^2)\rho DC^2/h$ (2). The substitution of the measured data (D), (C) and (h) into the variables in Formula (2) clarifies the relations between C (PWV) and E (Young's modulus of the wall), H (thickness of the wall) and D (diameter of the aorta) based on the 43 patients. In order to see which and how one of the three factors (D,h and E) would affect C, the standard deviation normalized by the mean of each variable (NSD) was calculated, and the correlations between C and D, h or E were obtained.

2. Results

The relationship between PWV and (1) the diameter of the aorta (D), (2) thickness of the aortic wall (h), and (3) Young's modulus of the aortic wall (E) were examined at a given constant minimum internal pressure at 80 mmHg based on the 43 patients of Sample B.

1) Diameter

Shown in Figure 5 is the correlation between the diameter (D) and PWV (C). The correlation coefficient (E) was -0.39, and the standard deviation, 0.15. A slightly negative trend was observed.

2) Thickness of the aortic wall

Presented in Figure 6 is the relation between the thickness of the aortic wall (h) and PWV (C). Because the correlation coefficient (*r*) was 0.15, and the standard deviation (NSD), 0.21, no significant association was observed.

3) Young's modulus of the aortic wall

Presented in Figure 7 is the relation between Young's modulus of the aortic wall (E) and PWV (C). A very high correlation was noted between E and C, with 0.93 of correlation coefficient (*r*) and standard deviation (NSD), 0.56.

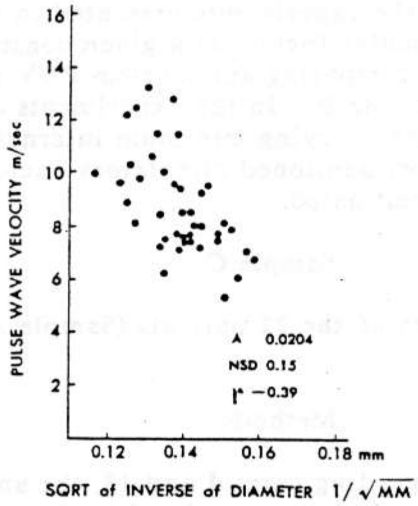


Fig. 5. Relation between pulse wave velocity and SQRT of inverse of diameter

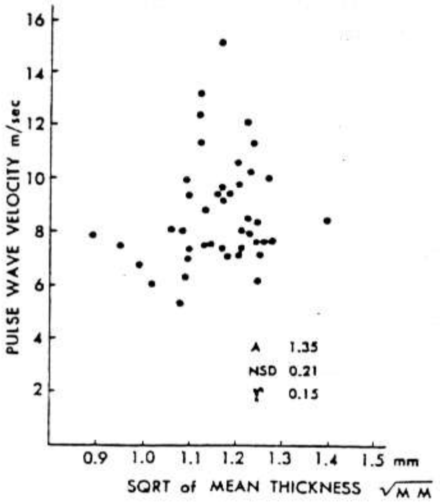


Fig. 6. Relation between Pulse wave velocity and SQRT of mean thickness

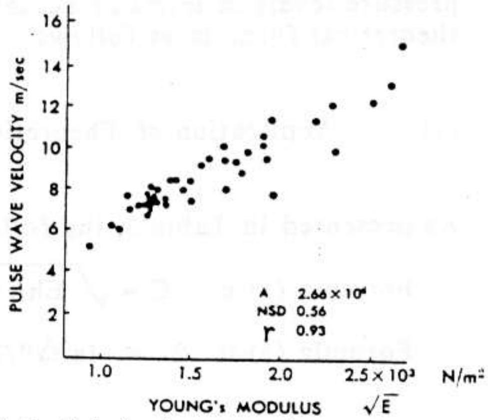


Fig. 7. Relation between pulse wave velocity and SQRT of Young's modulus

3. Summary

1) Both the diameter of the aorta and the thickness of the aortic wall were only very slightly influential over PWV and negligible as vascular factors affecting PWV.
2) Among the vascular factors under a given constant minimum internal pressure, the Young's modulus of the aortic wall (E) was very closely correlated with PWV (C) ($r = 0.93$). C may be regarded as representing E.

IV. EXAMINATIONS OF VASCULAR FACTORS UNDER VARYING MINIMUM INTERNAL PRESSURE (OR DIASTOLIC PRESSURE)

1. Materials and Methods

In the experiments presented in the preceding chapter, the effects on PWV of vascular factors at a given constant minimum internal pressure were examined by comparing antemortem PWV and postmortem PWV based on 43 subjects (Sample B). In the experiments described in this chapter, the vascular factors under varying minimum internal pressure were examined and both the aforementioned circulatory factors and the main factors which affect PWV are investigated.

1) Sample C

Two of the 22 patients (Sample A), namely cases 4 and 13 were used as Sample C.

2) Methods

Regarding cases 4 and 13, the analysis of the four circulatory factors had already been completed in the previous analysis, and the relationship between PWV and the minimum internal pressure has been known. In order to examine the effects of three vascular factors on PWV under changing minimum internal pressure levels in terms of actual measurements obtained are applied to the theoretical formula as follows:

(1) Application of Theoretical Formula (Table 3)

As presented in Table 3, the following equations were used:

Formula (1) is $C = \sqrt{Eh/(1 - \sigma^2)\rho D}$, and

Formula (3) is $\Delta r = [a^2 \Delta P / E(b^2 - a^2)] \times [(1 - \sigma - 2\sigma^2)r + (1 + \sigma)b^2/r]$

where:

E: Young's modulus of the aortic wall
: Poisson's ratio (1.06 g/cm)
: Blood viscosity (0.5)
D: Mean diameter of the aorta
h: Mean thickness of the aortic wall (b - a)
r: Mean radius of the aorta (b + a)
b: Outer radius of the aorta
a: Inner radius of the aorta
P: Intra-arterial pressure
C: Pulse wave velocity (PWV)

Table 3. Moens-Korteweg's equation (1) and Nakayama's equation (3)

$$C=\sqrt{Eh/(1-\sigma^2)\rho D} \tag{1}$$

$$E=(1-\sigma^2)\rho DC^2/h \tag{2}$$

$$\Delta r=[a^2\Delta P/E(b^2-a^2)]\times[(1-\sigma-2\sigma^2)r+(1+\sigma)b^2/r] \tag{3}$$

$$E=(1-\sigma^2)\rho C^2(b+a)/(b-a) \tag{4}$$

$$\left.\begin{aligned}da/dp&=2ab^2/(a+b)^2C^2\\ db/dp&=2a^2b/(a+b)^2C^2\end{aligned}\right] \tag{5}$$

Formula (3) expresses the amount of displacement r directed toward the radius of the aorta at the point (*r* *w*) when the internal pressure has an increase of p and can be derived from the theory of material dynamics[40,41] when the length of the cylinder is very long as compared to its radius, and the displacement in the axial direction is assumed to be zero. In Formula (3), if P is very small, (E = constant) is not substantiated. And a (internal radius), h (thickness of the aortic wall), and r (mean radius) are expressed as the function of the internal pressure, P. When h = b - a and D = b + a, Formula (2) $E = (1 - \sigma^2)\rho DC^2/h$ becomes Formula (4) $E = (1 - \sigma^2)pC^2(b + a)/(b - a)$. The calculation of displacement of a and b, or da and db, with $\Delta P \rightarrow dp$, gives Formula (5) $da/dp = 2ab^2/(a + b)^2C^2$ and $db/dp = 2a^2b/(a + b)^2C^2$. Formula (5) is the system of equation of a and b at dp, and if the initial conditions of C(P) (which expresses the relation between PWV and change in the internal pressure), a (internal radius) and b (external radius) are given, equations can be solved.

(2) Items examined (Table 3)

Based on the data such as a) the measurements (diameter and thickness of the aortic wall after isolation, and PWV at each minimum internal pressure in the perfusing experiment, b) invariableness of the external radius/internal radius ratio (b/a) (see IV-2-4, Results and VII-2, Discussion), and c) the diameter of the aorta and thickness of the aortic wall after isolation which were mostly consistent with the values at the internal pressure of 50 mmHg, a/a_1 and h/h_1 (h = b - a) at each pressure were calculated by Formula (5):

$$da/dP = 2ab^2/(a + b)^2C^2$$

$$db/dP = 2a^2b/(a + b)^2C^2$$

where a_1 and h_1 are the normalized values, corresponding to a and b at the internal pressure of 50 mmHg after isolation. Therefore, a and h were 3.3 and 0.14 cm on Case 4, and 3.7 and 0.13 cm on Case 13, and the a and h could be calculated from the respective a/a_1 and h/h_1. Further E can be calculated by substituting a and h into Formula (2), $E = (1 - \sigma^2)\rho DC^2/h$. Variations in (1) pulse wave velocity, C, (2) internal radius, a, (3) thickness of the aortic wall, h, (4) external radius/internal radius ratio, b/a, and (5) Young's modulus of the aortic wall with variations in the internal pressure, P, were examined by the above-mentioned methods.

2. Results

Regarding Cases 4 and 13, the effects of the vascular factors were examined according to every change of 10 mm/Hg in the minimum internal pressure ranging from 50 to 130 mmHg. The results are summarized as follows:

1) Pulse wave velocity, C (Figure 8 and Table 5)

Under the minimum internal pressures of 50, 80, 110 and 130 mmHg, the corresponding PWV values were 6.7, 7.9, 8.8, and 9.8 m/sec. on Case 4, and 7.4, 9.9, 15.0 and 25.1 m/sec. on Case 13, namely, the rate of an increase in PWV was greater on Case 13 than on Case 4.

2) Internal radius, a (Figure 9 and Table 5)

Under the minimum internal pressures of 50, 80, 110 and 130 mmHg, the corresponding internal radius measurements were 3.30, 3.43, 3.35 and 3.61 cm on Case 4, and 3.70, 3.82, 3.89 and 3.91 cm on Case 13. This shows a tendency that the internal radius increases along with an increase in the internal pressure. However, an increase in the internal radius resultant from an increase in the internal pressure from 50 to 130 mmHg was as small as 0.31 cm on Case 4 and 0.21 cm on Case 13. The rate of variation in the internal radius was 8.6% on Case 4 and 5.4% on Case 13.

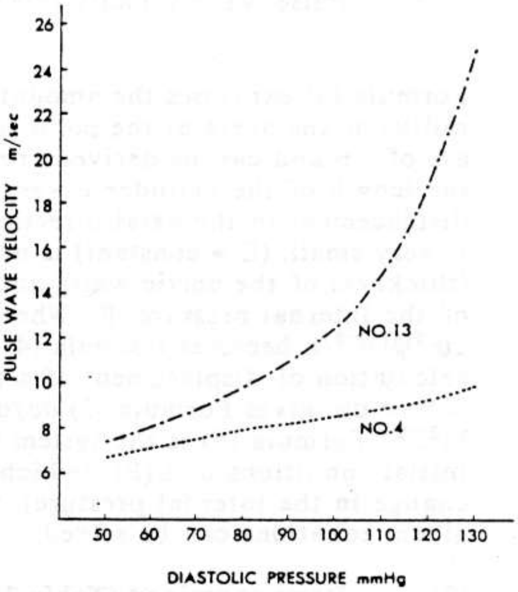


Fig. 8. Relation between pulse wave velocity and diastolic pressure (No. 4 and 13)

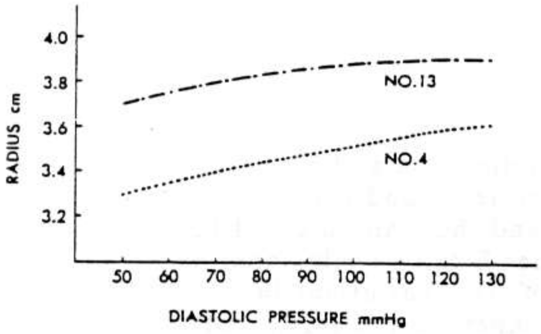


Fig. 9. Relation between radius calculated and diastolic pressure (No. 4 and 13)

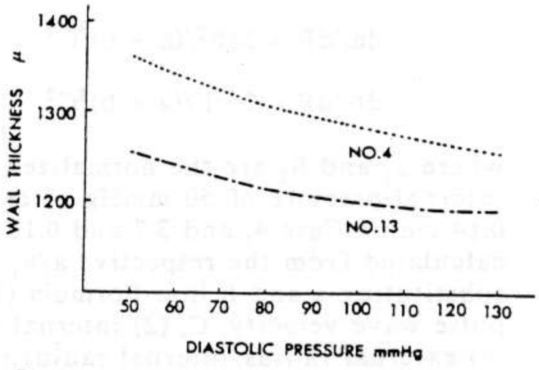


Fig. 10. Relation between thickness calculated and diastolic pressure (No. 4 and 13)

Table 4. Outer to innner radius ratios at various pressures calculated after Nakayama's equation for which the measured values at 50 mmHg were substituted.

	No. 4				No. 13			
P	a	h	b	b/a	a	h	b	b/a
50	3.30	0.14	3.44	1.0424	3.70	0.13	3.83	1.0351
60	3.35	0.13	3.48	1.0388	3.74	0.12	3.86	1.0321
70	3.40	0.13	3.53	1.0382	3.79	0.12	3.91	1.0317
80	3.43	0.13	3.56	1.0379	3.82	0.12	3.94	1.0314
90	3.45	0.13	3.58	1.0377	3.85	0.12	3.93	1.0312
100	3.51	0.13	3.64	1.0370	3.88	0.12	4.00	1.0310
110	3.55	0.13	3.68	1.0366	3.89	0.12	4.01	1.0309
120	3.58	0.13	3.71	1.0363	3.90	0.12	4.02	1.0308
130	3.61	0.13	3.74	1.0360	3.91	0.12	4.03	1.0333

P : intraarterial pressure (mmHg)
a : inner radius (cm)
b : outer radius (cm)
h : wall thickness (cm)

Table 5. Inner radii, thicknesses, Young's moduli and PWVs at various diastolic pressures calculated after Nakayama's and Moens-Korteweg's equations for which the measured values at 50 mmHg were substituted.

	P	a/a_1	h/h_1	E/E_1	a	h	E	PWV
No. 4	50	1.000	1.000	1.00	3.30	1362	2.31	6.7
	60	1.015	0.987	1.10	3.35	1344	2.54	7.1
	70	1.029	0.975	1.25	3.40	1328	2.89	7.5
	80	1.042	0.965	1.35	3.43	1308	3.12	7.9
	90	1.045	0.954	1.50	3.45	1299	3.47	8.2
	100	1.056	0.945	1.70	3.51	1287	3.93	8.5
	110	1.076	0.937	1.85	3.55	1276	4.27	8.8
	120	1.085	0.929	2.05	3.58	1265	4.47	9.3
	130	1.049	0.922	2.35	3.61	1255	5.43	9.8
No. 13	50	1.000	1.000	1.00	3.70	1256	3.17	7.4
	60	1.012	0.989	1.15	3.74	1242	3.65	8.1
	70	1.023	0.979	1.35	3.79	1230	4.28	8.9
	80	1.032	0.972	1.65	3.82	1220	5.23	9.9
	90	1.040	0.965	2.10	3.85	1212	6.66	11.1
	100	1.047	0.960	2.90	3.88	1205	9.19	12.5
	110	1.050	0.956	4.35	3.89	1200	13.79	15.0
	120	1.055	0.953	6.05	3.90	1197	19.18	19.2
	130	1.057	0.951	7.90	3.91	1194	25.04	25.1

E : Young's modus ($\times 10^{6} N/m^{2}$)
a : inner radius (cm)
h : thickness (μ)
P : intraarterial pressure (mmHg)
E_1, a_1 and h_1 : each value of E, a and h in 50 mmHg min. press.
PWV : Pulse Wave Velocity (m/sec)

3) Thickness of the aortic wall, h (figure 10 and Table 5)

Under the minimum internal pressures of 50, 80, 110 and 130 mmHg, the corresponding thickness of the aortic wall tended to decrease from 1362 to 1308, 1276, and 1255 micrometer (or Mm) on Case 4, and from 1256 to 1220, 1200 and 1194 micrometer (or Mm) on Case 13. However, the amount of a decrease in the thickness of the aortic wall with an increase in the minimum internal pressure from 50 to 130 ,mmHg was as small as 107Mm on Case 4 and 62 Mm on Case 13. The rate of variation in the thickness of the aortic wall was 7.9 on Case 4 and 4.9% on Case 13.

4) The External/Internal Radius Ratio, b/a (Table 4)

Despite variations in the internal pressure, the external/internal radius ratio remained almost stable on both Case 4 and Case 13, with the range of 1.0360 to 1.0424 on Case 4 and 1.0333 to 1.0351 on Case 13 when the minimum internal pressure ranged from 50 to 130 mmHg.

5) Young's Modulus of the Aortic Wall (Figure 11)

Under the minimum internal pressures of 50, 80, 110 and 130 mmHg, the corresponding values of Young's modulus of the aortic wall were 2.31, 3.21, 4.27, and 5.43 (x 10^6 N/m^2) on Case 4, and 3.17, 5.23, 13.79 and 25.04 (x 10^6N/m^2) on Case 13. The increase between 50 and 130 mmHg was 2.12 x 10^6N/m^2 on Case 4, and 21.87 x 10^6 N/m^2 on Case 13. Young's modulus of the aortic wall markedly increased as having an increase in the internal pressure. Further, when the degree of nonlinearity was compared between the two cases, an increase by 58% was noted on Case 4 (that had low PWV) but an increase by 91% on Case 13 (that had a high PWV). Accordingly, the degree of nonlinearity was greater on Case 13.

3. Summary

1) Changes observed in the internal radius of the aorta and the thickness of the aortic wall according to changes in the minimum internal pressure was so small that they were negligible.

2) The external/internal radius ratio remained almost stable, even if changes occurred in the minimum internal pressure.

3) The pulse wave velocity is expressed by Young's modulus of the aortic wall which varies with changes in the minimum internal pressure, and the higher the pulse wave velocity, the greater the degree of its nonlinearity.

V. COMPARISON OF ANTEMORTEM AORTIC PULSE WAVE VELOCITY (PWV) WITH POSTMORTEM PWV

1. Materials and Methods

The antemortem pulse wave velocity of eight subjects (Table 1) were compared with the postmortem PWV of the same subjects to examine if PWV measured on the isolated aortas after death were consistent with the antemortem PWV.

1) Sample D

By using the isolated aortas from eight patients, the experiment on artificial PWV was conducted. The PWV of these patients were available for study.

2) Methods

The antemortem PWV or diastolic pressure was measured and was determined at the minimum internal pressure or diastolic pressure. From this and the pulse wave velocity-minimum internal pressure curve obtained in the postmortem experiments, the correlation between the antemortem PWV and the postmortem PWV was calculated by Pearson's method.

2. Results

As presented in Figure 12, the correlation coefficient (*r*) between the antemortem and postmortem PWV values was 0.98, and the standard deviation, 0.52. It was proved that PWV measured by suing the isolated aortas was the almost exactly the same as PWV measured before death.

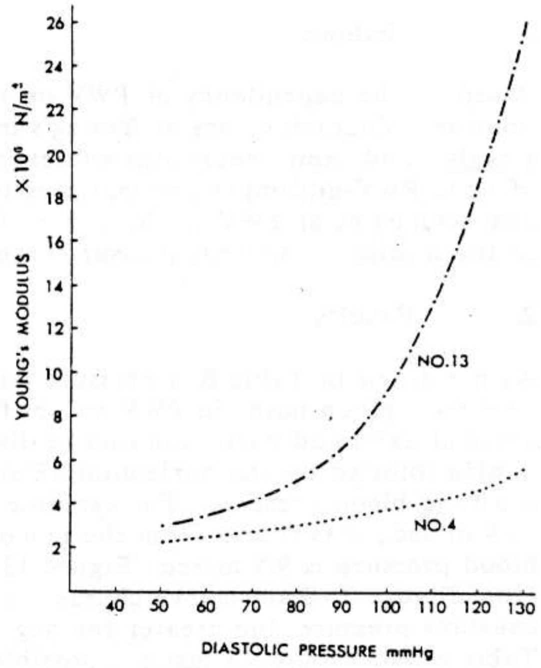


Fig. 11 Relation between Young's modulus calculated and diastolic pressure (No. 4 and 13)

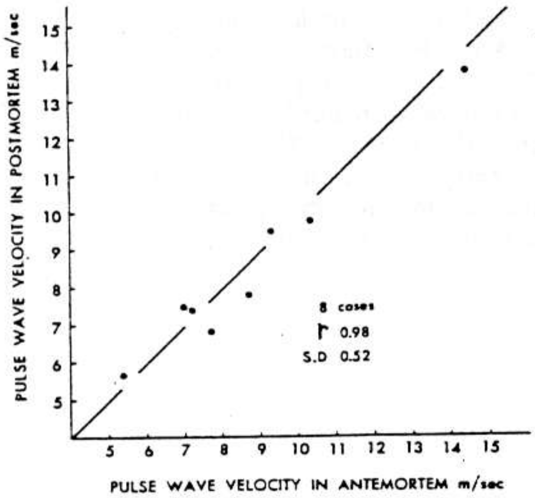


Fig. 12. Pulse wave velocity in ante- and post-mortem (8 cases)

VI. DEVELOPMENT OF PRESSURE NOMOGRAM TABLE

1. Materials and Methods

The aortic PWV of a living subject varies according to the minimum internal pressure (or diastolic pressure) at the time of measurement. For this reason, the measurements in situ cannot be compared with one another on the same criterion unless they are normalized to pressure. This section describes the preparation of the pressure nomogram which permits the normalization of the measurements in situ to a given constant diastolic pressure, based on the basic data obtained in II to V described earlier.

1) Materials

The PWV-diastolic pressure curves obtained from the examination of 22 isolated aortas were used (Table 1 and Figure 2).

2) Methods

Based on the dependency of PWV on the minimum internal pressure, the nonlinear characteristics of Young's modulus of the aortic wall (see IV-2 Results) and their theoretical evidence presented, the degree of the nonlinearity of each PWV-minimum internal pressure curve was examined. The curve characteristics of PWV in the range of 5.0 to 14.0 m/sec associated with changes in the minimum internal pressure from 50 to 130 mmHg are expressed as models.

2. Results

As presented in Table 6, a pressure nomogram was developed. It enables us to convert a given point in PWV values from 5.2 to 14.0 m/sec. (plotted on the vertical axis) and corresponding to diastolic blood pressure from 50 to 108 mmHg (plotted on the horizontal axis) into PWV standardized at 80 mmHg of diastolic blood pressure. For example, if PWV at 98 mmHg diastolic pressure is 10.8 m/sec., it is found from the nomogram that PWV at 80 mmHg of diastolic blood pressure is 9.5 m/sec. Figure 13 presents the conversion models stemmed from Figure 2. Each curve characteristics show that the higher PWV under a constant pressure, the greater the degree of nonlinearity in the curve. These Table 6 and Figure 13 made it possible to normalize all measurements at 80 mmHg, and thus a comparison of PWV among individuals is possible.

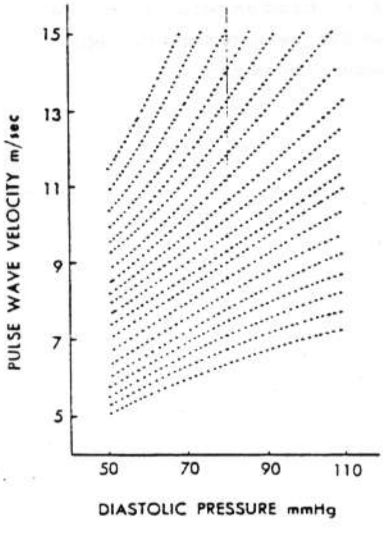


Fig 13

PULSE WAVE VELOCITY m/sec	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	82	84	86	88	90	92	94	96	98	100	102	104	106	108
14.0															14.4	13.8	13.5	13.1	12.9	12.7	12.7	12.5	12.3	12.1	11.8	11.7	11.5	11.3	11.2
13.8														14.6	14.1	13.6	13.3	12.9	12.8	12.5	12.4	12.2	11.9	11.7	11.6	11.5	11.3	11.2	11.0
13.6													14.8	14.4	14.0	13.4	13.1	12.8	12.6	12.4	12.2	12.0	11.8	11.5	11.5	11.4	11.1	11.0	10.9
13.4												15.0	14.7	14.2	13.8	13.1	13.0	12.7	12.4	12.2	12.0	11.8	11.6	11.4	11.3	11.2	11.0	10.9	10.8
13.2											15.0	14.8	14.3	14.0	13.6	13.0	12.8	12.4	12.3	12.0	11.8	11.7	11.5	11.3	11.2	11.0	10.9	10.8	10.7
13.0										15.2	14.9	14.4	14.1	13.8	13.4	12.8	12.5	12.2	12.1	11.9	11.6	11.5	11.4	11.2	11.1	10.9	10.8	10.7	10.6
12.8										15.1	14.8	14.1	13.9	13.4	13.2	12.6	12.4	12.1	12.0	11.7	11.5	11.4	11.2	11.0	10.9	10.8	10.6	10.6	10.5
12.6									15.2	15.0	14.5	14.0	13.7	13.3	12.9	12.4	12.2	12.0	11.9	11.6	11.3	11.2	11.1	10.9	10.7	10.6	10.3	10.4	10.3
12.4									15.0	14.8	14.1	13.8	13.4	13.1	12.7	12.2	12.0	11.9	11.8	11.5	11.2	11.1	11.0	10.8	10.6	10.5	10.5	10.3	10.1
12.2								15.1	14.8	14.4	13.8	13.6	13.1	12.8	12.5	12.0	11.9	11.6	11.4	11.2	11.1	10.9	10.8	10.6	10.5	10.4	10.3	10.1	10.0
12.0								14.8	14.5	14.1	13.4	13.2	13.0	12.5	12.3	11.8	11.7	11.4	11.2	11.1	10.9	10.7	10.6	10.4	10.3	10.2	10.1	10.0	9.8
11.8							15.0	14.6	14.0	13.9	13.2	13.0	12.6	12.3	12.1	11.7	11.5	11.2	11.1	11.0	10.8	10.6	10.5	10.3	10.2	10.1	10.0	9.8	9.7
11.6						15.2	14.8	14.2	13.8	13.6	12.9	12.7	12.4	12.2	11.8	11.5	11.2	11.0	10.9	10.7	10.6	10.4	10.3	10.1	10.0	9.9	9.8	9.7	9.6
11.4						14.8	14.2	13.8	13.5	13.1	12.7	12.5	12.3	11.9	11.7	11.2	11.1	10.8	10.7	10.6	10.4	10.3	10.2	10.0	9.9	9.8	9.7	9.6	9.5
11.2					14.8	14.6	13.9	13.6	13.2	12.8	12.5	12.3	12.0	11.7	11.4	11.0	10.8	10.7	10.6	10.4	10.3	10.1	10.0	9.9	9.8	9.7	9.5	9.4	9.3
11.0				15.0	14.7	14.1	13.7	13.3	12.9	12.5	12.2	12.0	11.7	11.5	11.2	10.8	10.6	10.5	10.4	10.2	10.1	10.0	9.8	9.7	9.6	9.5	9.4	9.3	9.2
10.8			14.8	14.7	14.2	13.6	13.3	13.0	12.6	12.4	11.9	11.6	11.5	11.2	11.0	10.6	10.5	10.3	10.1	10.0	9.9	9.8	9.6	9.5	9.4	9.3	9.2	9.1	9.0
10.6		15.1	14.7	14.2	14.0	13.4	13.0	12.8	12.3	12.2	11.7	11.4	11.2	11.0	10.8	10.5	10.3	10.2	10.0	9.8	9.7	9.6	9.5	9.4	9.3	9.2	9.1	8.9	8.8
10.4	15.6	14.8	14.1	13.8	13.5	13.0	12.5	12.4	12.2	11.8	11.6	11.2	10.9	10.8	10.6	10.3	10.1	10.0	9.9	9.7	9.6	9.5	9.3	9.2	9.1	9.1	9.0	8.8	8.7
10.2	15.1	14.1	13.8	13.4	13.0	12.9	12.3	12.2	11.6	11.5	11.2	10.9	10.7	10.6	10.4	10.1	9.9	9.8	9.7	9.6	9.4	9.3	9.2	9.0	8.9	8.8	8.6	8.6	8.5
10.0	14.5	13.8	13.5	12.9	12.8	12.4	12.2	11.8	11.5	11.2	10.9	10.7	10.5	10.4	10.2	9.9	9.7	9.6	9.5	9.3	9.2	9.1	9.0	8.8	8.7	8.6	8.5	8.5	8.4
9.8	14.0	13.4	13.1	12.6	12.4	12.2	11.9	11.4	11.2	10.9	10.6	10.5	10.4	10.1	10.0	9.7	9.6	9.4	9.3	9.2	9.0	8.9	8.8	8.7	8.6	8.5	8.4	8.4	8.3
9.6	13.5	13.0	12.5	12.3	12.0	11.8	11.4	11.1	11.0	10.6	10.4	10.3	10.2	9.9	9.8	9.5	9.4	9.3	9.1	9.0	8.8	8.7	8.6	8.5	8.4	8.4	8.3	8.2	8.1
9.4	13.0	12.5	12.2	12.0	11.5	11.4	11.0	10.8	10.6	10.4	10.1	10.0	9.8	9.7	9.6	9.3	9.2	9.1	9.0	8.8	8.6	8.5	8.4	8.3	8.2	8.2	8.2	8.1	8.0
9.2	12.5	12.2	11.9	11.6	11.2	11.0	10.7	10.5	10.4	10.1	9.9	9.8	9.6	9.5	9.4	9.1	9.0	8.9	8.8	8.5	8.4	8.4	8.3	8.2	8.1	8.0	7.9	7.9	7.8
9.0	12.2	11.8	11.6	11.2	10.8	10.6	10.4	10.3	10.1	9.9	9.7	9.6	9.4	9.3	9.2	8.9	8.8	8.6	8.5	8.4	8.3	8.2	8.1	8.0	7.9	7.9	7.8	7.8	7.7
8.8	11.8	11.5	11.2	10.9	10.5	10.4	10.1	9.9	9.8	9.7	9.5	9.4	9.2	9.1	9.0	8.7	8.6	8.4	8.3	8.2	8.2	8.1	8.0	7.9	7.8	7.8	7.7	7.7	7.6
8.6	11.4	10.7	10.8	10.6	10.4	10.2	10.0	9.7	9.6	9.5	9.3	9.2	9.0	8.9	8.8	8.5	8.4	8.3	8.2	8.1	8.0	7.9	7.8	7.8	7.7	7.7	7.6	7.5	7.4
8.4	11.0	10.5	10.3	10.2	10.0	9.8	9.6	9.5	9.3	9.2	9.1	9.0	8.8	8.7	8.6	8.3	8.2	8.1	8.0	7.9	7.8	7.8	7.7	7.6	7.5	7.5	7.4	7.4	7.3
8.2	10.5	10.3	10.1	9.9	9.7	9.6	9.4	9.3	9.2	9.0	8.8	8.7	8.6	8.5	8.4	8.1	8.0	7.9	7.8	7.7	7.6	7.6	7.5	7.5	7.4	7.3	7.2	7.2	7.1
8.0	10.2	10.0	9.8	9.7	9.5	9.4	9.2	9.1	9.0	8.8	8.7	8.6	8.4	8.3	8.2	7.9	7.8	7.7	7.6	7.6	7.5	7.4	7.3	7.3	7.2	7.2	7.1	7.0	6.9
7.8	9.8	9.7	9.6	9.4	9.3	9.2	9.0	8.9	8.8	8.6	8.4	8.3	8.2	8.1	8.0	7.7	7.6	7.6	7.5	7.4	7.3	7.3	7.2	7.1	7.0	7.0	6.9	6.8	6.7
7.6	9.7	9.5	9.3	9.2	9.1	9.0	8.8	8.6	8.5	8.4	8.2	8.1	8.0	7.9	7.8	7.5	7.4	7.4	7.3	7.2	7.1	7.1	7.0	6.9	6.8	6.8	6.7	6.7	6.6
7.4	9.4	9.2	9.2	9.0	8.8	8.7	8.6	8.5	8.4	8.2	8.0	7.9	7.8	7.6	7.5	7.4	7.3	7.2	7.1	7.1	7.0	6.9	6.8	6.7	6.6	6.6	6.5	6.5	6.4
7.2	9.2	9.1	8.9	8.7	8.6	8.5	8.3	8.2	8.0	7.9	7.8	7.7	7.6	7.5	7.4	7.2	7.1	7.0	6.9	6.8	6.7	6.7	6.6	6.6	6.5	6.5	6.4	6.4	6.3
7.0	9.0	8.7	8.7	8.5	8.4	8.3	8.2	8.0	7.8	7.7	7.6	7.5	7.4	7.2	7.1	6.9	6.8	6.8	6.7	6.7	6.6	6.6	6.5	6.4	6.3	6.3	6.2		
6.8	8.7	8.6	8.4	8.3	8.2	8.0	7.8	7.7	7.6	7.5	7.4	7.3	7.1	7.0	6.9	6.7	6.6	6.6	6.5	6.5	6.4	6.3	6.2						
6.6	8.5	8.4	8.3	8.1	7.9	7.8	7.2	7.5	7.4	7.2	7.1	7.0	6.9	6.8	6.7	6.6	6.5	6.4	6.3										
6.4	8.3	8.2	8.0	7.9	7.6	7.5	7.4	7.3	7.1	6.9	6.8	6.8	6.7	6.6	6.5	6.3	6.2												
6.2	8.0	7.8	7.8	7.6	7.4	7.3	7.2	7.0	6.8	6.7	6.6	6.5	6.5	6.4	6.3														
6.0	7.8	7.6	7.5	7.3	7.2	7.0	6.9	6.8	6.6	6.5	6.4	6.3	6.2																
5.8	7.5	7.4	7.2	7.1	6.9	6.7	6.6	6.5	6.4	6.3	6.2																		
5.6	7.3	7.1	6.8	6.8	6.6	6.4	6.4																						
5.4	6.8	6.7	6.5	6.4	6.3																								
5.2	6.4	6.4																											

DIASTOLIC PRESSURE mmHg

Table 6. Nomogram for normalization of PWV at a given constant blood pressvre (80mmHg)

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