Volume-Pressure Curves of the Human Arm

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After interruption of the circulation, pressure changes in the brachial artery and a forearm vein were recorded and plotted against volume of blood injected intra-arterially expressed in ml./100 cc. of arm tissue. The resulting volume-pressure curves showed a steep rise with the first injection, a linear rise in the center section and a rapid increase during the last injection. These curves were not influenced by either sex, age or moderate systemic hypertension.

The volume-pressure curves of various vascular beds have been determined in vivo in animals, but as far as we know, no direct studies in human beings have been performed. While studying the asystolic pressure gradient and the critical closing pressure,1 we developed a technic suitable for the direct determination of a volume-pressure curve of the vascular bed of the human arm.

Method

Fifty-eight subjects of both sexes and various ages, predominantly in the 30 to 40-year age group, were studied. The subjects had no clinical evidence of cardiovascular disease except for 5 who had systemic arterial hypertension.

The subjects were recumbent and dressed in ordinary indoor clothing. The right arm was extended horizontally at an angle of 45° with the forearm 5 cm. below a plane passing through the fourth costochondral junction. Indwelling Cournand needles were inserted into the brachial artery and into a suitable forearm vein and connected to Hathaway pressure gages through three-way stopcocks. Pressures were recorded photographically.

One hundred milliliters of blood were drawn with 10 ml. syringes heparinized with 0.1 ml. commercial heparin. A 5 cm. wide compression cuff was placed with the lower border 5 cm. above the cubital fold. After a 30 sec. interruption of circulation, blood was injected into the brachial artery in 10 ml. units. The rate of injection was kept constant—as closely as possible to 1 ml./sec., and the intervals between injections were 10 sec. Immediately after completion of each injection simultaneous arterial and venous pressures were recorded. In the last 26 cases, venous pressures were omitted since our earlier results indicated that the curves for venous and arterial pressures were similar after the first 20 ml. injected.

In 7 subjects the blood was injected into the arm vein instead of the brachial artery. In 5 subjects the arterial volume-pressure curve was repeated after the venous system had been allowed to fill by inflating the cuff to 50 mm. Hg for 2 min. In 3 subjects, once the total volume of blood had been injected, an "extraction curve" was obtained by aspirating blood from the venous system.

Results

No pain was felt during the first intra-arterial injections, but after 60 or 70 ml. of blood had been injected, the subjects complained of a disagreeable, bursting sensation in the forearm and hand that increased with subsequent injections, but disappeared immediately after deflating the cuff. A few subjects developed petechiae, which was the only vascular phenomenon observed.

The volume-pressure curves can be seen in figure 1. The venous pressures were omitted for the sake of clarity, but they followed very closely the arterial curve except that in the first injection the venous pressure did not increase at the same rate as the arterial. It can be seen that in most curves the first injection caused a significant rise in arterial pressure, whereas the second injection induced either no change or a fall in pressure. Then an almost linear increase in pressure followed the subsequent injections, at a rate of approximately 10-15 mm. Hg per injection. No marked differences were observed between old and young subjects. The results for a small group of hypertensives (5 patients) showed no significant differences from the normal. The volume-pressure curves done on the same subjects on different days were found to be entirely reproducible.

In the volume-pressure curves taken after the venous pressure had been raised to 50 mm. Hg by compression, the second injection did not elicit the peculiar flattening or fall in pres-
In three cases, an "extraction curve" was compared with the "injection curve" (fig. 2). The former parallels the latter, starting at the same point, but shifted to the right. The total amount of blood extracted was 80 per cent of the volume injected. The final arterial pressure was approximately 20 mm. Hg.

In 7 subjects blood was injected into a vein instead of into the brachial artery (fig. 3). Venous pressure was remarkably high following the first injection. A definite pain response was immediately apparent. Subsequent injections often induced marked decreases in venous pressure. The arterial pressure increased slowly and remained much lower than the venous pressure even after a total of 100 ml. of blood had been injected.

**DISCUSSION**

The flattening of the arterial pressure curve after the first 10 ml. were injected could be explained by the sudden opening of some of the vessels (arterioles?) previously closed by the "active tension" developed by the smooth muscle in vessels of small diameter and decreased internal pressure. This hypothesis is supported by the results of the experiments performed with an initial pressure of 50 mm. Hg, in which linear increases were observed from the very beginning. However, in curves recorded in different venous beds of animals, a similar flattening was observed. It was attributed to the fact that the smooth muscle of the venous wall can only oppose small pressures.

The increase in slope found in most of our cases after 70 to 80 ml. of blood had been injected reveals a decrease in the volumetric elasticity of the vascular bed, the fibrous jacket of the adventitia probably playing a major role in this phenomenon. Furthermore, the volume-pressure curves obtained in the human forearm with an indirect method by Greenfield and Patterson also showed a steeper slope starting at similar pressures. Because of the different elastic property of veins and arteries, the venous bed is distended after the first injections. Therefore, the slope of the curve would be determined by the arterial side only. Capillaries behave as rigid tubes once the
internal pressure has surpassed the critical closing pressure.\textsuperscript{7}

In our “extraction curves” the decreased volume recovered, and the lower slope could be explained by (a) escape of fluid into the tissues during the high pressure phase, and (b) delayed elasticity (hysteresis) of the vascular structures.\textsuperscript{8} The existence of an arterial pressure level of approximately 20 mm Hg after no more blood can be secured from the vein could be attributed to a critical closing pressure of the small vessels.

The presence of valves in the veins does not permit comparison of results of the intravenous with the intra-arterial injection. The sudden decrease in venous pressure, after the initial increase is evidence of valvular incompetence when the intravascular pressure exceeds certain limits. Alexander\textsuperscript{9} did not register arterial pressure variations during venous injections as we have observed; however, in his experiments pressures above 60 mm Hg were not reached. In other vascular beds, without valves as in the lung, no differences have been observed whether blood was injected intra-arterially or intravenously.\textsuperscript{10}

With regard to the pain, it is interesting to note that it appeared immediately after intra-venous injection, but only after more than 70 ml had been injected intra-arterially. The same pain response to acute venous distention has been elicited by small inflated balloons placed within the veins.\textsuperscript{11}

With the very high pressures attained in some patients, which must have been exerted on all the vessels of the segment, it was surprising that confluent petechiae and ecchymoses were not more commonly observed. The frail walls of the capillaries might be assumed to be incapable of resisting the pressures exerted, sometimes over 200 mm Hg. However, Burton\textsuperscript{5} has pointed out that the tension in the wall of a vessel is related both to the applied pressure and to its radius according to Laplace’s equation $T = PR$. Since the radius of the capillaries is 10,000 times smaller than that of large arteries, the tension exerted on the walls of capillaries is correspondingly and remarkably small.

**Summary**

A study of the volume-pressure curves of the vascular bed of the human forearm and hand was performed on 58 subjects. Up to 100 ml of autologous, heparinized blood was reinjected intra-arterially in 10 ml aliquots after circulation had been interrupted by means of a cuff. Pressure changes in the brachial artery and a forearm vein were recorded, and plotted against volume injected in ml./100 cc. of arm tissue. The resulting arterial and venous volume-pressure curves obtained showed a steep rise with the first injection, a linear rise in their center section with a rapid increase during the last injections. Neither sex, age, nor moderate systemic hypertension seemed to alter this curve appreciably. “Extraction curves,” volume-pressure curves after venous engorgement and intravenous injection curves were also obtained.

**SUMMARIO IN INTERLINGUA**

Un studio del curvas representante le relation de volumine a pression in le vasculatura del antebrazo e del mano esseva executate in 58 subjectos. Usque a 100 ml de heparinisate sanguine autologe esseva reinjicite intra-arterialmente in partes aliquot de 10 ml post que le circulation habeva essite interrumpite per medio de un manchette. Alterationes de pression in le arteria brachial e un vena del bracio inferior esseva registrate e representate graphicamente como function del volumine del injection exprimite in ml per 100 cm$^3$ de tessuto. Le resultante curvas del relation de volumine a pression in arteria a vena monstrava un acute elevation post le prime injection, un ascension linear in le section central, e un augmento rapide durante le ultime injectiones. Ni le sexo del subjecto, ni su etate, ni mesmo le presentia de moderate grados de hypertension systemic influentiava iste curvas de maniera appreciabile. Esseva etiam obtenite “curvas de extraction,” curvas del relation de volumine a pression post replenation venose, e curvas de injection intravenose.

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_Circ Res._ 1957;5:236-239
doi: 10.1161/01.RES.5.3.236

_Circulation Research_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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