HYDRAULIC POWER STUDIES OF DYNAMIC REACTIONS IN THE PERIPHERAL VASCULAR BED

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Summary : The peripheral resistance analysis for the study of hemodynamics in the peripheral vascular bed has been critically examined. The resistance concept has been shown to lead to information about vessel calibre changes only. In order to overcome the limitation the hydraulic power concept has been introduced and the rationale discussed. For the specific case of the hind limb of the dog the hydraulic power concept has been applied to demonstrate that vasoactive drugs besides altering vessel calibre change the elasticity and viscosity properties of the small arterial and arteriolar regions of the peripheral vascular bed. Acetylcholine in particular increases vessel calibre and reduces wall viscosity. The changes for adrenaline indicate opposing trends leading to insignificant net change in wall physical properties even though the calibre markedly reduces.

Key words : peripheral vascular bed, acetylcholine, adrenaline, peripheral resistance, hydraulic power, vessel calibre, elasticity, viscosity

INTRODUCTION

Local mechanims in circulatory control and optimum capillary exchange being related(5), considerable research has been directed towards studying the effects of neurogenic activity, metabolic activity and drug administration on blood vessels. The changes in viscoelasticity occuring in larger arteries, for example the femoral artery, has been investigated under static and dynamic stretch by Petersen (6) and others. The small arteries, arterioles and sphincters pose a completely different set of problems due to the small size and complexity in the structural network. Direct measurements as made on larger arteries is not practicable *in vivo* for small vessels. But this region is the major contributor to circulatory control. In view of the physiological importance of the region extensive studies have been carried out using the well known concept of peripheral resistance (3) and the section consisting of the small arterioles have come to be arteries and known as resistance vessels (2).

The resistance data has been used for drawing conclusions regarding vascular constriction and dilitation and also for describing the general state of vascular smooth muscles. If no pulsatility were to exist in the resistance vessels the use of peripheral resistance would be quite satisfactory. Alternatively if the strees—strain properties of vascular wall were linear and time independent

under all states of the vascular control mechanisms, the conclusions drawn purely on the basis of equivalent vascular resistance would be valid. In the actual system neither of these conditions exist. There exists substantial research to show that pulsatile pressure does exist in arterioles (8). Past work on larger arteries have shown that the extent of strain depends on the stress, that is, the elasticity modulus varies with the degree of stress (1). In addition, the stress is time dependent and exhibits a hysteresis effect (9). For example following a rapid stretch there is fast rise in tension and then an exponential decay. These deviations from conditions necessary for using resistance for vascular studies makes it imperative to study the resistance vessels under dynamic conditions.

A direct and precise study of the physical properties of resistance vessels under dynamic conditions is not feasible with techniques available at present. It is however possible to obtain considerable information of the resistance vessels in an integrated manner from pulsatile blood flow and pressure measurements in larger artery just proximal to the resistance vessels. The present paper gives the basis of such a methods and gives the results of studies of the effect of administration of adrenaline and acetylcholine.

THEORY

The heart transfers pulsating mechanical energy to the pumped out mass of blood. If the vascular bed of the hind limb is to be studied the 'Windkessel vessels' would consist mainly of the aorta, iliac artery and the femoral artery (4). The pressure and flow in the femoral artery are a combined effect of the forces transmitted from the heart throught the 'Windkessel vessels' and the reactions from the peripheral vascular bed. For instance, if reflections from the peripheral vascular bed are reduced by adding a damping system, the wave patterns in the fermoral artery are affected. The combination of pressure and flow in the femoral artery therefore also contains information regarding the state of the peripheral vascular bed. A suitable way of examining pressure and flow in a combined form is to calculate the hydraulic energy transfer per unit of time which is same as hydraulic power. The hydraulic power is the product of blood pressure and blood flow rates.

Three distinct components of power are associated with the tranference of hydraulic energy. They are :—

1) Steady frictional effects and losses due to branching of the arterial tree and termed non pulsatile active power.

2) Viscous dissipation in vessel walls and surrounding tissue during pressure pulsations and termed pulsatile active power.

3) Mechanical reaction power of vascular tissue and termed pulsatile reactive power. This form of power is transferred back and forth between the blood mass and vascular tissue without producing any net dissipation.

Past physiological investigations focussed attention only on the mean values of pressure nd flow through computation of peripheral resistance. Thus only frictional effects and branch- ng effects were taken into account. No information about the state of the vascular wall was ontained in the resistance data except for the general information regarding constriction r dilatation. The pulsating form of energy takes into account dynamic effects.

MATERIALS AND METHODS

Experiments : Blood pressure and flow recordings in eleven mongrel dogs (10 to 14 *kg*) naesthetized with sodium pentobarbital (30 *mg/kg*) intravenously were used to evaluate the ydraulic power components. Anticoagulation was obtained with sodium heparin at 5 *mg/kg* dministered intravenously. A 15 cm long cannulating loop of polyethylene tubing was placed n the left femoral artery through an incision. The loop included the cannula of a laboratory abricated sine wave flowmeter, a T-tube for lateral pressure measurement and a short segment f thick walled rubber tubing for injection of drugs. Blood from the proximal end of the emoral artery after passing through the cannulating loop was fed into the distal end of the rtery. Pressure waves were obtained with a P23AA statham strain gauge manometer. The requency response of the flow and pressure measuring system under actual experimental onditions was flat within $\pm 5\%$ in a range of 0 to 20 cps. Femoral artery of the right hind leg as also cannulated but without recording devices.

Half an hour after the anaesthetic, when cardiovascular status of the animal had tabilised, control recordings were taken following the injection of 0.2 *ml* isotonic (0.9%) saline nto the cannulating loop in the peripheral direction. Within one min after this 2 μg of drenaline in 0.2 *ml* of saline was injected and records were taken again. After about 10 min esponse to 2 μg of acetylcholine in 0.2 *ml* of saline was recorded.

Subsequently 2 μg of adrenaline and 2 μg of acetylcholine each in 0.2 *ml* of saline were injected in the right femoral artery and the effect on the pressure and flow in the left femoral artery was observed.

In four animals a 12 cm long polyethylene tubing (1.4 cm i.d.) was included in the distal segment of the cannulating loop of the left leg. Control recordings were taken with only about 1 cm of this tubing inserted into the artery and then following maximal intertion of the tubing into the artery. The length of maximal insertion was around 7 cm. Thus the viscoelastic large arterial segment was replaced by relatively rigid polyethylene tube.

Calculations : The hydraulic power transmitted via blood is equal to the product of the pressure and flow rate since the pressure represents force and the flow rate represents movement. The product of instantaneous pressure and instantaneous flow rate gives instantaneous power, but summation of the instantaneous power values has no physical significance in relation to hydraulic power in a cardiac cycle. Therefore special mathematical techniques have to be

adopted to calculate the power from the pressure and flow data. The simplest method is to split up mathematically the pressure and flow separately into their harmonic contents. Fourier analaysis may be adopted. The pressure, for example, will have an average value plus a sine wave component having a frequency equal to the heart rate and other sine waves having frequencies which are integral multiples of the first wave. The product of the mean values of the pressure and flow gives the non-pulsatile active power. In order to obtain the pulsatile active and pulsatile reactive powers the relative phase positions of individual harmonics of the same frequency in the pressure and flow have to be considered. Product of the in-phase components gives the pulsatile active power and the product of the out of phase (by 90°) components gives the pulsatile reactive power. productof pressure and flow of different frequencies has no physical significance as the net contribution during a total cardiac cycle is zero. The calculations in their mathematical form is given in the appendix.

For a typical calculation of power the time period of the cycle was divided into a number of equal time intervals each of the order of 0.025 second. The pressure and flow recordings were quantitated at the boundary points of these intervals. These data were used to calculate power components as indicated in the appendix using a digital computer.

To assess the normal variability in power, four cycles were analysed in a control record for five dogs. In each dog the cardiac cycles were selected so as to avoid any bias especially due to respiration. Similarly to get a picture of the progressive effect of the drugs, several cardiac cycles were analysed for these dogs. For the other dogs the cardiac cycle to be analysed in the control record was selected at random and for the drug effects a cycle preceding the maximum flow effect point by 3 to 7 cardiac cycles was selected for reasons given later.

RESULTS

The magnitude of the pulsatile active power was greater than the pulsatile reactive power. But with the injection of acetylcholine there was a progressive increase in the pulsatile power ratio, that is, the ratio of the reactive pulsatile power to the active pulsatile power. After that the ratio decreased. The increase in the pulsatile power ratio with acetylcholine is statistically significant. The non-pulsatile active power increases. With the administration of adrenaline the non-pulsatile active power decreased, but the changes in the pulsatile power are not significant, The control data is given in Table I. For the same animals the response to acetylcholine is given in Table II and response to adrenaline in Table III.

Variability from cycle to cycle within a control record was within $\pm 7.5\%$ for power. Hence this variability may be neglected without affecting the conclusion.

TABLE I : Hydraulic power under control conditions.

g No.	NACP	ACP	RCP	PPR
1	101.55	10.44	2.97	0.285
2	76.58	9.57	6.59	0.688
3	63.61	5.22	3.77	0.722
4	54.02	6.59	5.64	0.855
5	67.40	8.62	2.71	0.314
6	68.99	4.53	1.98	0.437
7	72.57	2.92	1.94	0.664
8	134.64	5.07	3.06	0.603
9	68.82	11.21	5.15	0.459
0	89.13	4.27	1.79	0.419
1	61.00	5.87	3.50	0.596
vg.	78.02	6.75	3.55	0.549
E.M.	±6.91	±0.83	±0.48	±0.056

or abbreviations asee appendix

TABLE II : Hydraulic power after acetylcholine administration.

Dog No.	NACP	ACP	RCP	PPR	% Change in PPR*	Change in ACP*	% Change in RCP*
	209.66	7.65	3.24	0.423	48.42	—26.72	9.09
	209.14	5.07	6.71	1.323	92.29	—47.02	1.82
	180.09	1.95	3.05	1.564	116.62	—62.24	—19.09
	232.76	5.52	3.19	0.577	-32.51	—16.23	—43.43
	179.91	6.83	4.24	0.620	97.45	—20.76	56.45
	148.98	4.74	2.94	0.620	41.87	4.63	48.48
	121.44	2.97	2.66	0.895	34.78	1.71	37.11
	265.29	2.01	2.03	1.009	67.33	—60.35	—33.66
	157.79	12.09	8.18	0.676	47.27	7.85	58.84
	219.16	2.44	1.73	0.709	69.21	—44.02	—3.35
	204.81	2.63	1.93	0.733	22.98	—55.19	—44.85
vg.	193.54	4.90	3.62	0.832	55.06	—28.98	6.13
E.M.	±12.35	±0.93	±0.61	±0.103	±12.92	±8.39	12.43
P					<0.002	<0.01	<0.6n.s.

TABLE III : Hydraulic power after adrenaline administration.

Dog No.	NACP	ACP	RCP	PPR	% Change in PPR*	% Change in ACP*	% Change in RCP*
1	34.41	9.13	2.53	0.277	—2.80	—12.54	—14.81
2	17.58	11.49	6.69	0.582	—15.40	20.60	1.52
3	6.37	5.29	3.18	0.601	—16.75	1.34	15.64
4	2.25	7.91	7.06	0.892	4.32	20.03	25.17
5	33.12	9.76	3.49	0.357	13.69	1.32	28.78
6	0.00	4.31	1.79	0.415	—5.03	—4.85	—9.59
7	0.00	3.46	2.52	0.728	9.63	18.49	29.89
8	78.26	5.17	2.25	0.435	—27.86	1.97	—26.47
9	34.56	11.81	5.16	0.436	—5.01	5.35	0.19
10	28.85	3.95	1.80	0.455	8.59	—7.49	0.55
11	1.46	5.50	2.91	0.529	—10.23	—6.30	—16.85
Avg.	21.53	7.07	3.58	0.518	—4.26	3.40	3.09
S.E.M.	±7.18	±0.92	±0.56	±0.052	±4.03	±3.47	±5.87
P					>0.2n.s.	>0.2n.s.	>0.5n.s.

NACP, ACP, RCP are in mm. Hg. x ml/sec. n.s. Not significant

For other abbreviations see appendix

$$* \ \%\text{Change} = \frac{\text{Experimental—Control}}{\text{Control}} \times 100$$

DISCUSSION AND CONCLUSIONS

It has been observed that when 2 μg of adrenaline or acetylcholine was injected into the right femoral artery the effect on the left femoral arterial blood flow was negligibly small and the time lapse between administration of the drug and its effect on the left arterial flow was much longer than the time interval between injection in the left femoral artery and the changes in the hydraulic power in that leg. Therefore, the changes in power shown in the table are mainly due to changes in the vascular bed rather than due to effects of the circulated drug on the heart.

Insertion of tubing maximally into the distal end of the femoral artery reduced all components of power proportionately and the trends following drug administration were not altered. Hence it may be concluded that the effect studied are distal to the large arterial section, that is, in the small arterial and arteriolar regions.

The increase in the non-pulsatile active power following administration of acetylcholine would be expected as it is known that acetylcholine acts on the beta dilator receptors

ding to dilitation and increased flow. Such an increase has actually been observed. But pulsatile active power following administration of acetylcholine decreases significantly, reas there is no significant change in the pulsatile reactive power. The latter indicates that the low dose level used the elastic modulus does not change significantly. The reduction in active pulsatile power can therefore be ascribed to reduction in the hysteresis effect of the scular smooth muscles following dilitation. That is, the effective viscosity is reduced. ch effects are known to occur in the larger arteries. The consideration of pulsatile draulic energy leads to information regarding change in blood vessel hysteresis due to tylcholine. In contrast traditional peripheral resistance concept can only lead to the nclusion that acetylcholine leads to vessel dilitation (4) and provides no information on e effect of the drug on wall properties as for example hysteresis losses.

If the vascular system were linear and the vascular wall behaviour identical for e steady state as well as dynamic events, the effects for adrenaline would have en exactly opposite to that of acetylcholine. For the non-pulsatile part the changes llowing adrenaline administration are opposite to that of acetylcholine, that is, the n-pulsatile active power decreases. The pulsatile components do not present a pattern of ange opposite to that of acetylcholine effect. This clearly shows that the dynamic fects do differ from static effects as given by the peripheral resistance concept.

Reduction in the non-pulsatile active power following adrenaline administration is cause total frictional losses decrease due to the marked reduction in mean flow. As it is own that adrenaline acts both on alpha and beta receptors (10) for the dosage level used, e balance of effect is toward vasoconstriction. However, it is not necessary for all regions of e peripheral vascular bed to have constricted in order to produce reduction in flow. A nstriction in the small arterial region would have a similar effect. The pulsatile com- nent progressively gets damped as it travels from the large artery to the capillaries. There- re no significant change in pulsatile active and pulsatile reactive power indicates that in mall arterial region adrenaline does not produce a net change in elasticity or viscosity. the arteriolar region along with constriction, change in elasticity and hysteresis would cur. But here too marked vasoconstriction would lead to deformation of wall structures ther than muscle. Hence effect of changes in elasticity and viscosity of muscles would be asked. The present study shows that the hydraulic power concept is a more powerful ol than the peripheral resistance concept for study of vascular responses particularly due drug administration. In addition to providing information regarding changes in vessel alibre the power concept demonstrates that the elasticity and viscosity of the vessel walls lso change. On the other hand the peripheral resistance data does not contain information garding vessel wall properties. Further work, analysing by the hydraulic power approach ta following administration of selective receptor blocking agents in combination with soactive drugs will precisely indicate the changes in wall elasticity and viscosity separately.

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APPENDIX

The product of pressure (force/area) and flow rate (volume/time) has the physical dimensions of power (work or energy/time). Hence the product of the amplitude of a particular frequency in the pressure and flow waves is proportional to the power for that frequency. The constant of proportionality will depend on the phase angle between the pressure and flow.

Although the pressure and flow waveforms are not true periodic functions of time, they may be approximated to periodic functions. Hence by the fourier series analysis technique, the pressure (P) can be expressed as:

$$P(t) = \frac{a_0'}{2} + \sum_{p=1}^{M} [a'_p \text{ COS } 2\pi fpt + b'_p \text{ SIN } 2\pi fpt] \qquad (1)$$

where p is the harmonic number, M is the highest harmonic under consideration (in the present study M = 5) and f is the fundamental frequency. The coefficients a_0, a_p and b_p can be calculated for discrete values of P (t) using a digital computer (7).

From expression (1)

$$P(t) = \frac{a_0'}{2} + \sum_{p=1}^{M} A'_p \text{ SIN } (2\pi fpt + \phi'_p)$$

$$A'_p = \sqrt{(a'_p)^2 + (b'_p)^2} \qquad \phi'_p = \text{ARCTAN}\left(\frac{a'_p}{b'_p}\right)$$

Similarly the flow (F) can be expressed as

$$F(t) = \frac{a_0''}{2} + \sum_{p=1}^{M} A''_p \text{ SIN } (2\pi fpt + \phi''p) \qquad (2)$$

$$A''p = \sqrt{(a''_p)^2 + (b''_p)^2} \qquad \phi''p = \text{ARCTAN}\left(\frac{a''p}{b''p}\right)$$

Therefore.

$$\text{Nonpulsatile active power (NACP)} = \frac{a_0'}{2} \times \frac{a_0''}{2}$$

Pulsatile active power for p^{th} harmonic (ACP_p)

$$= \left| \frac{A'_p A''_p}{2} \text{ COS } (\phi_p' - \phi_p'') \right|$$

Pulsatile reactive power for the p^{th} harmonic (RCP_p)

$$= \left| \frac{A'_p A''_p}{2} \text{ SIN } (\phi_p' - \phi_p'') \right|$$

$$\text{Pulsatile active power (ACP)} = \sum_{p=1}^{M} \text{ACP}_p$$

$$\text{Pulsatile reactive power (RCP)} = \sum_{p=1}^{M} \text{RCP}_p$$

$$\text{Pulsatile power ratio (PPR)} = \text{RCP}/\text{ACP}$$

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