Direct Measurements of Right and Left Heart Outputs in a Valsalva-Like Maneuver in Dogs[1] (36378)

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Because the performance of variants of the Valsalva maneuver is an everyday occurrence in animals, *e.g.*, during defecation, coughing, parturition, etc., and because this maneuver has been used as a diagnostic tool, the study of the hemodynamic changes produced by this maneuver has long attracted the attention of physiologists. Realizing that these are not identical maneuvers, this study was nevertheless undertaken in the hope that investigation of the Valsalva-like maneuver devised for use in anesthetized dogs (15), may elucidate the mechanisms underlying the hemodynamic changes of the Valsalva maneuver since this former maneuver circumvented the restrictions against the use of sophisticated instrumentation.

Methods. In dogs flowmeter probes (10, 18) were implanted at the roots of the pulmonary artery and aorta and the central end of a polythene tube, sealed with wax at both ends, was inserted into the left atrial appendage for later use in catheter placement. One to 3 weeks later when flow signals were satisfactory (6, 16, 22), under Na pentobarbital (30 mg/kg), catheters for pressure measurement were advanced into the pulmonary artery, right and left atrium, and into the ascending aorta. Positive pressure respiration ($<$15 cm H_2O) at 24/min was used in the prone animals except during the maneuvers.

Flowmeter signals were recorded using a base line-holding circuit (17) and calibrated by dye curves and a meaned flowmeter signal of high sensitivity as described previously (18). This procedure calibrates the aortic flow probe as left heart output rather than as ascending aorta flow. The continuous measurement of left and right heart outputs for the first time permits the continuous measurement of changes in pulmonary blood volume, actually volume between the flowmeter probes, even under nonsteady-state conditions.

Compressed air under 40 mm Hg pressure was applied simultaneously to both the trachea and to a sphygmomanometer cuff around the chest wall of the dog (15) and maintained for 20 sec. All pressures (referred to midchest level), the ECG and the flows were recorded on a photo-oscillograph as well as stored on magnetic tape.

Measurements of flows and pressures were made at 1 sec intervals from electronically meaned pressure and flow recordings (Fig. 2), beginning 4 sec before and continuing for 40 sec following onset of the maneuvers. Because the changes in intrapleural pressure during the maneuver would be expected to be large in comparison to the difference between the right and left atrial pressure changes, comparisons of atrial pressures with heart output were made following the Valsalva-like maneuvers so that the atrial pressures would reflect transmural pressures. Only relative heart output was determined from the ratio of the area of the instantaneous flowmeter signal to the area for this signal during the control period, both areas being normalized for cycle length. Mean values for atrial pressure and relative heart output measured over an entire respiratory cycle were used. Mean atrial pressures have been shown to correlate closely with ventricular end-

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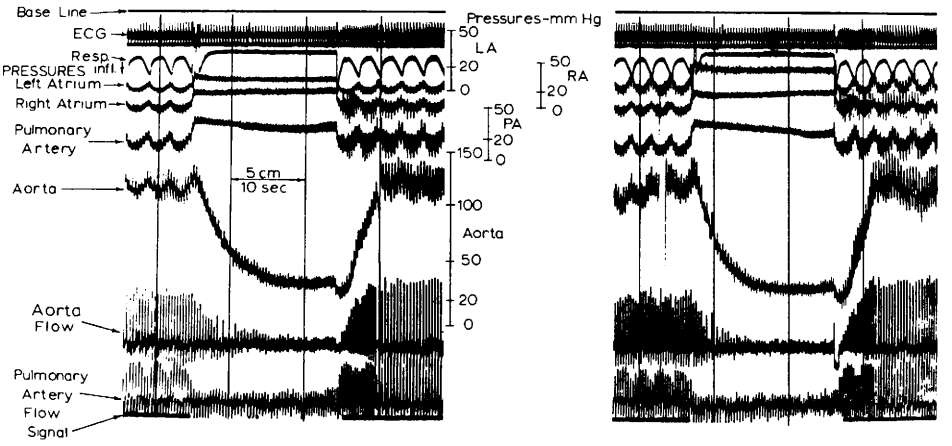

FIG. 1. Simultaneous recordings of the changes in instantaneous left and right heart outputs as well as the changes in the pressures before, during and following two Valsalva-like maneuvers (40 mm Hg positive pressure for 20 sec) from the same experiment. Note the marked decrease in aortic pressure and the earlier and more precipitous fall and recovery of the right compared to the left heart output.

diastolic pressures (14).

Results. Seven satisfactory Valsalva-like maneuvers were obtained in 2 of 26 dogs operated. In the remaining dogs complete data were not obtainable because of probe failure, rupture of the great vessels or reduction in QRS amplitude which prevented recording and/or retrieving of the flowmeter signals triggered by the QRS.

Recordings of the changes in the flowmeter signals and pressures recorded before, during and after two Valsalva-like maneuvers performed in the same experiment are shown in Fig. 1. Note the marked fall in aortic pressure following onset of the maneuver. The mean aortic pressure preceding the seven Valsalva-like maneuvers averaged 112 (range: 108–116) mm Hg; mean pulmonary artery pressure 12 (range: 11–14) mm Hg and, at autopsy, no areas of atelectasis or pleural effusions were noted.

The meaned as well as the instantaneous left and right heart flows and the meaned pressures recorded before, during and after the Valsalva-like maneuver shown in the left panel of Fig. 1 are shown in Fig. 2. Pressure

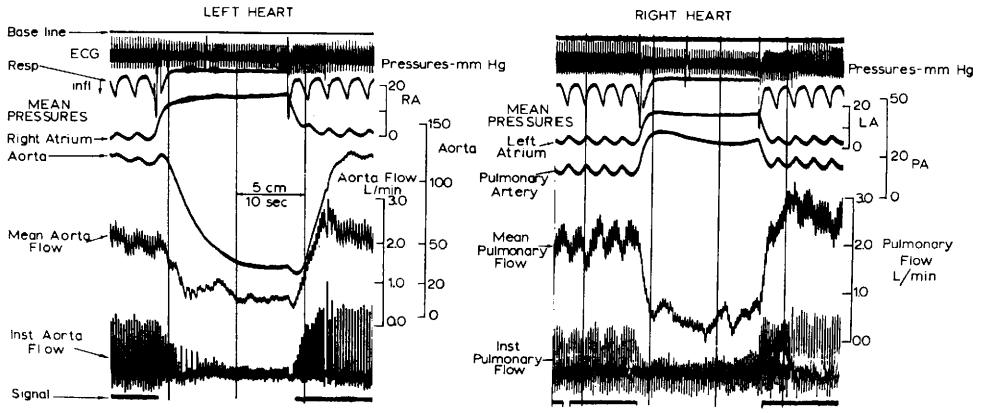

FIG. 2. Recordings of changes in meaned left and right heart outputs and pressures produced by the Valsalva-like maneuver shown in the left panel of Fig. 1. Flow and pressure measurements were made from such electronically meaned recordings unless otherwise indicated.

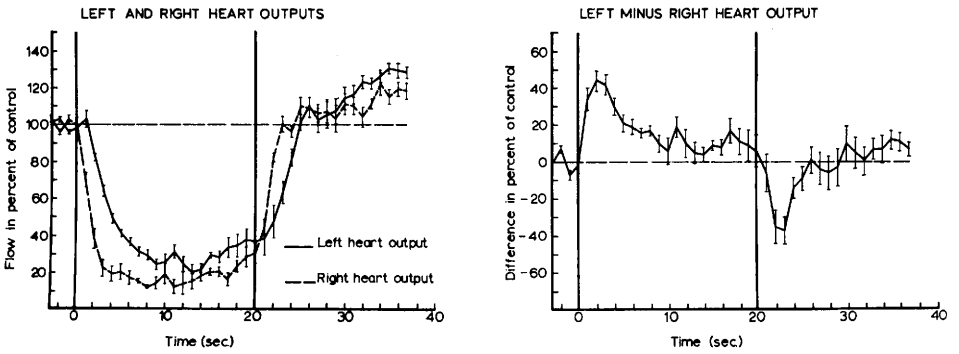

FIG. 3. (a; left panel) Comparison of changes in mean left and right heart outputs (% of their control value) from 7 Valsalva-like maneuvers performed in two experiments. Note the earlier, more precipitous fall and recovery of the right heart output and that the right heart output fell to a lower value than the left. (vertical lines) ± standard errors of the mean. (b; right panel) Plot of the mean difference between left and right heart outputs (% of their control value) before, during and after 7 Valsalva-like maneuvers. Note that early in the maneuver the left heart output greatly exceeds the right while shortly after the maneuver the reverse is true. (vertical lines) ± standard errors of the difference, *e.g.*, $(SE^2_a + SE^2_b)^{1/2}$. The plot of the mean difference between left and right atrial pressures in mmHg (not shown) resemble this plot.

changes closely similar to those seen during the maneuvers in this report were found in 11 additional maneuvers in 3 other experiments in which one or both of the flow signals was unsatisfactory.

Mean values for the left and right heart flows, in percent of their control values, are shown in the left panel of Fig. 3. Mean control flows were 2.69 and 2.53 liters/min for the left and right heart, respectively, which were considered identical ($p > .1$).

The onset of the fall in right heart flow preceded that of the left heart flow by an average of 2 beats (range: 1 to 3 beats) while, after the maneuvers, the onset of the return of the right heart output toward normal again preceded that of the left heart output by an average of 2 beats (range: 1 to 4 beats). It took an average of 2 beats (range: 1 to 2 beats) for the right heart flow to fall to a steady level after onset of the maneuver and an average of 3 beats (range: 2 to 3 beats) for the flow to return to a steady level after conclusion of the maneuver. Contrariwise, comparable values for the left heart were an average of 7 beats (range: 5 to 8 beats) for flow to fall to a steady level after onset of and an average of 14 beats (range: 13 to 16 beats) for flow to return to a steady level after the maneuver. Figure 3 shows that the right heart output fell to a consistently lower value than the left, the mean right heart output during the last 10 sec of the maneuver being 20 ± 2% while that of the left heart was 30 ± 2% of control value.

The mean difference between left and right heart outputs (% of their control value) is shown in the right panel of Fig. 3 and is positive during the maneuver because of the greater fall in right than in left heart output. Note the early marked positive value and the reversal of this difference, *i.e.*, the right heart output greatly exceeding that of the left, shortly after the maneuver. By multiplying the mean percentage difference between left and right heart outputs during the maneuver by the control flow for a 20 sec period, a mean decrease in pulmonary blood volume of 140 ± 45 ml ($p < .02$) or of approximately 40%[2] was calculated.

As shown in Fig. 4, the course of the differ-

[2] Pulmonary blood volume was calculated as 15% of the total blood volume, the latter taken as 92.5 ml/kg. The justification for calculating these pulmonary blood volume changes although the left atrial and ventricular volumes are included in our measurement is that changes in the volume between the probes are felt to reflect changes in pulmonary rather than in heart chamber volume.

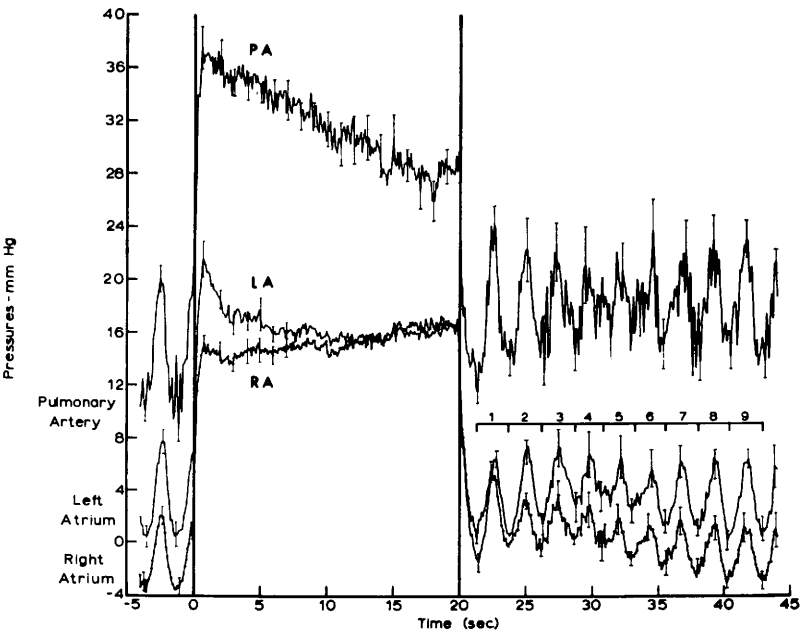

FIG. 4. Comparison of changes in mean left and right atrial as well as pulmonary artery pressures before, during and after 7 Valsalva-like maneuvers performed in two experiments. (vertical lines) ± standard errors of the mean. The successive respiratory cycles following the maneuver were delineated and numbered as shown. During the maneuver, note the fall of left atrial pressure at the same time as the right atrial pressure was progressively rising to exceed the former. In the first cycle following the maneuver, note the slight phase shift between right and left atrial pressures with the right atrial pressure leading. Also note immediately following the Valsalva-like maneuver the elevation of the right atrial pressure with its subsequent gradual decrease and the diminution of left atrial pressure with its rapid increase toward control value. The pulmonary artery pressure is seen to lie below airway pressure (40 mm Hg) and to decrease progressively during the maneuver.

ences in changes in the atrial pressures generally mirrored that of the flows. Left atrial pressure was higher than right early when the left heart output greatly exceeded the right, while the right atrial pressure increased greatly relative to the left near the end of the maneuver, when the right heart output was increasing relative to the left and actually exceeded the left atrial pressure just after the maneuver, a time when the right heart output greatly exceeded the left. This change in the difference between the atrial pressures was highly significant ($p < .001$). Left atrial pressure fell rapidly after onset of the pulmonary inflation, its fall mirroring the fall in left heart stroke volume (Figs. 1 and 2), after which it stabilized. Right atrial pressure, contrariwise, rose gradually throughout the maneuver until, near its end and shortly thereafter, it actually exceeded the left. After the maneuver, mean left atrial pressure, initially somewhat low (3 mm Hg), rapidly rose to its control value (4 mm Hg) while mean right atrial pressure, initially elevated (3 mm Hg), did not approach its control value (—1 mm Hg) until 9 respiratory cycles later. In the first respiratory cycle after the maneuver, a slight phase shift between the atrial pressures, with the right leading to the left, is evident in Fig. 4.

Changes in heart output are compared with the changes in atrial pressure in Fig. 5. The data from the left heart (Fig. 5a), numbered and plotted sequentially from the first respiratory cycle after the maneuver (Fig. 4), reveal that the points appear to lie on two ventricular function curves. During the first three respiratory cycles, with the left atrial

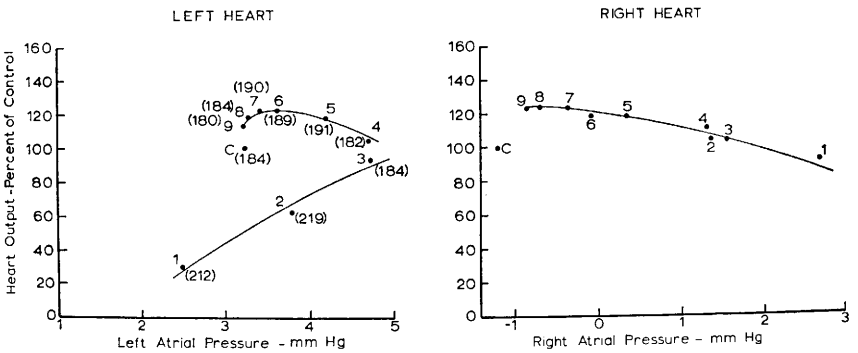

FIG. 5. (a; left panel) Comparison of left heart output (% of control), and left atrial pressure for the successive respiratory cycles after the Valsalva-like maneuver numbered as in Fig. 4. Each point represents the mean values for relative heart output and left atrial pressure measured over a whole respiratory cycle from the 7 maneuvers. Note that left atrial pressure begins below its control value *C*. The points appear to lie on two ventricular function curves, the first three points forming a classical Starling curve while, beginning with the fourth cycle, as left atrial pressure decreases, there is at first a rise in stroke volume. The numbers in parentheses are the mean heart rates during the particular respiratory cycles. (b; right panel) Comparison of right heart output (% of control) and right atrial pressure plotted as in left panel. Note that the right atrial pressure begins considerably above its control value *C*. The points appear to lie on the down-slope of a single ventricular function curve.

pressure beginning below and rising above control value, increasing left atrial pressure was associated with an increase in heart output as in the classical Frank–Starling mechanism. Beginning with the fourth respiratory cycle, the decreasing left atrial pressure was actually accompanied, for a time, by an increase in heart output which then gradually approached the control value. The right heart plot (Fig. 5b) reveals, beginning with an elevated right atrial pressure, a progressive increase in heart output with decreasing right atrial pressure which is suggestive of these points forming the down-slope of a ventricular function curve. As shown in Fig. 5a, the heart rate increased appreciably only in the first two respiratory cycles after the maneuver during which increases of 15 and 19%, respectively, above control value occurred.

The pressure–flow ratios for the pulmonary and systemic vascular beds showed an early increase in the pulmonary pressure–flow ratio to 1100 ± 300% of control which then leveled off near 500% of control towards the end of the maneuver. There was a much smaller diphasic change in the systemic pressure–flow ratio, an early small rise above control (+25%) being followed by a slightly larger fall below control (—60%).

Discussion. A comparison between the changes in thoracic aorta flow during Valsalva maneuvers performed by conscious humans (4) and the changes in left heart output during Valsalva-like maneuvers performed on our anesthetized dogs showed these to be closely similar during all 4 stages of these maneuvers (see Table I). The major differences were that the systemic arterial pressure fell much more markedly and that the atrial and pulmonary arterial pressures rose less markedly in the Valsalva-like maneuvers, these differences causing the marked difference in the changes in the systemic pressure–flow ratio produced by them. This contrasts with earlier findings that the results of "Valsalva maneuvers" performed under general anesthesia "were qualitatively and quantitatively similar to those in conscious dogs" (9).

The cause of this difference in systemic pressure fall may have been any one or more of the following: (a) Basic differences between the maneuvers, *e.g.*, their probably different effects on intrapleural and intraabdominal pressures, etc.; (b) probable species

TABLE I. Comparison of the Effects of the Valsalva-Like and Valsalva Maneuvers on Systemic Flow, Systemic and Pulmonary Arterial and Atrial Pressures, Heart Rate and Other Physiologic Variables.

	Valsalva-like maneuver[a] in dog		Valsalva maneuver[b] in man (4)		
	(liters/min)	(% of control)	(liters/min)	(% of control)	
Left heart output					Thoracic aorta flow
Control[c]	2.69		4.2		Control[e]
I[d]		88		97	I[d]
II		35		39	II
III		35		36	III
IV		106		107[e]	IV
Right heart output					
Control	2.53				
I		55			
II		26			
III		72			
IV		106			
Systemic arterial pressure (aortic)	(mm Hg)		(mm Hg)		Systemic arterial pressure (right subclavian)
Control	112		143/88		Control
I	115		161/102		I
II	28		108/83		II
III	23		95/73		III
IV	115		178/100		IV
Pulmonary artery pressure					Pulmonary artery pressure
Control	12		23/12		Control
I	24		53/46		I
II	23		50/44		II
III	15		22/11		III
IV	15		28/15		IV
Right atrial pressure					Superior vena cava pressure
Control	—1		7		Control
I	14		32		I
II	17		35		II
III	4		9		III
IV	2		9		IV
Left atrial pressure					
Control	4				
I	19				
II	16				
III	2				
IV	5				

TABLE I (continued).

	(beats/min)	(% of control)	(beats/min)	(% of control)	
Heart rate					Heart rate
Control	189		72		Control
I	187	99	65	90	I
II	203	107	97	135	II
III	214	113	105	146	III
IV	185	98	57	79	IV
Pressure/flow ratio systemic	(dyn sec cm^{-5})		(dyn sec cm^{-5})		Pressure/flow ratio in lower part of body
Control	3385		1990		Control
I		100		95	I
II		35		150	II
III		60		220	III
IV		100		115	IV
Pressure/flow ratio pulmonary					
Control	300				
I		190			
II		470			
III		165			
IV		120			

[a] 20 sec maneuver in anesthetized, prone dogs, airway pressure 40 mm Hg, breathing room air.

[b] 15 sec maneuver by conscious supine humans, airway pressure 40 mm Hg, breathing 100% O_2.

[c] Values determined during the 4 sec period immediately preceding the maneuver.

[d] According to Hamilton, Woodbury, and Harper (8): stage I = first 3 sec of maneuver; stage II = last 3 sec prior to release; stage III = 2–3 sec period of further pressure drop after release; stage IV = overshoot. These stages were readily identifiable and similar in the two types of maneuvers.

[e] In the abstract and in Table II of Ref. (4), this value is erroneously given as 119% (5.0 liters/min) when it should actually be 107% (4.6 liter/min).

differences in the vasodepressor reflexes released by pulmonary inflation in the dog and man (1, 2, 7, 23); (c) probable interference with the baroreceptor-mediated compensatory mechanisms by the anesthesia.

The large values for left minus right heart output, positive at the onset and negative after the maneuvers (Fig. 3), were due to the differences in the times of onset and in the rates of fall and rates of return to control value of the right and left heart outputs. As the difference in the area above compared to that below the zero line shows, the decrease in pulmonary blood volume incurred during the Valsalva-like maneuver was not fully restored in the first 20 sec or even in the first 60 sec (not shown) after the maneuver. Others have also reported a decrease in pulmonary blood volume from application of positive pressure to the airway (9).

Whereas there may be obstruction to systemic venous return in the Valsalva-like as in the Valsalva maneuver in humans (13, 15), the marked increase in the pulmonary pressure–flow ratio suggests another site of obstruction to flow in the Valsalva-like maneuvers, namely, at the small pulmonary vessels. In favor of the latter are: (a) The opposite time course of the right and left atrial pressures which suggests an obstruction to flow

between the atria. (b) The marked fall in right heart output within 1–2 heart beats after onset of the maneuver which suggests an obstruction to outflow from the right ventricle. (c) The simultaneous fall in pulmonary artery and rise in right atrial pressures (Fig. 4) which do not support inflow obstruction to the right heart as the major underlying mechansim.

The obstruction to pulmonary flow is believed to be due to the pressure surrounding the small pulmonary vessels, intra-alveolar pressure, exceeding both the pulmonary arterial and venous pressures as is seen to be the case in Fig. 4 (11, 12, 20, 21). The development of underperfused or unperfused alveoli in cats and in normal upright subjects who breathed against only a 20 cm H_2O positive pressure (3) supports this reasoning.

Progressive inability of the right ventricle to carry increased load could explain the fall in pulmonary artery pressure along with the rise in right atrial pressure during the maneuver. Evidence for such right heart insufficiency are the elevation in right atrial pressure immediately after the Valsalva-like maneuver (Fig. 4) and the suggestion that the points comparing right atrial pressure and right heart output lie on the down-slope of a ventricular function curve (Fig. 5b). The combination of a falling pumonary pressure–flow ratio, actually seen, and a progressively increasing systemic venous return offer an alternative explanation for the falling pulmonary artery and rising right atrial pressures.

In the plot of atrial pressure versus output for the left heart (Fig. 5a), the Frank–Starling mechanism apparently predominated during the first three respiratory cycles after the Valsalva-like maneuver, possibly because of myocardial hypoxia due to reduced coronary flow during the maneuver. From the fourth respiratory cycle on, neurohumoral effects are felt to have become the predominant factor controlling the output of the left heart. These atrial pressure versus heart output plots along with the brief phase shift between right and left atrial pressures immediately after the Valsalva-like maneuver strongly suggest that the Frank–Starling mechanism plays a role in the restoration of cardiac balance under these conditions.

Summary. While changes in systemic flow produced by Valsalva-like maneuvers in dogs closely resembled those of Valsalva maneuvers performed by humans, systemic arterial pressure fell much more in the Valsalva-like maneuvers as the pulmonary prssure–flow ratio rose markedly (+1100%). Right and left heart outputs decreased to 20 and 30% of control, respectively, while pulmonary blood volume decreased by 140 ± 45 ml or by approximately 40% in the Valsalva-like maneuver. The course of the atrial pressures, rapid fall in right heart output and development of acute right heart insufficiency suggest a hitherto unreported site of obstruction to flow in the Valsalva and Valsalva-like maneuvers, namely, at the small pulmonary vessels. Ventricular function curves and a phase shift between ventricular filling (atrial) pressures suggest that the Frank–Starling mechanism plays a role in restoration of cardiac balance after this maneuver.

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