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Pulsus Paradoxus *

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Previous studies from this laboratory (1–3) have shown that the paradoxical pulse of experimental cardiac tamponade is produced by an exaggerated inspiratory decline of left ventricular stroke volume. Most investigators have concentrated on one of three principal mechanisms of this inspiratory decrease of left ventricular stroke output. An early postulate (4) was that because of high intrapericardial pressure throughout the respiratory cycle, extrapericardial venous pressure falls more than atrial pressure during inspiration, thus reducing cardiac filling and stroke volume (5–7). With this mechanism, inspiratory pulmonary venous pooling would be expected to occur. A second major theory proposes that the tense pericardium is further stretched during inspiration by downward movement of the diaphragm and forward motion of the sternum, increasing cardiac compression and reducing filling of the left heart (8, 9). A third concept depends upon persistence of the normal inspiratory increase in right heart filling during cardiac tamponade. This increase in volume of the right heart and great vessels within the taut pericardial sac is believed to raise the intrapericardial pressure and thus hinder left heart filling by raising left atrial pressure (10, 11).

With any of the above three mechanisms, an inspiratory decrease of pressure gradient from pulmonary veins to left atrium would be expected and has been consistently reported (4–7). Thus, additional investigation is required to determine the fundamental mechanism responsible for the paradoxical pulse of cardiac tamponade. In our previous paper (2), exaggerated inspiratory decrease of left ventricular stroke output was demonstrated in cardiac tamponade, but the mechanism that interfered with left ventricular filling during inspiration was not identified. The studies to be described in this paper were designed to evaluate the significance of the following factors, which may reduce inspiratory left heart filling during cardiac tamponade and thus cause a paradoxical pulse: *1*) inspiratory rise of transpericardial pressure, *2*) inspiratory pooling of blood in the pulmonary veins, and *3*) inspiratory increase of venous return to the right heart.

The respiratory variation in transpericardial pressure was measured in dogs with cardiac tamponade both with and without controlled venous return to the right heart. Systemic venous return and right heart output were measured throughout the respiratory cycle before and during cardiac tamponade. Increased right heart filling and right ventricular output during inspiration would militate against diaphragmatic pericardial stretch as an essential mechanism interfering with left heart filling during inspiration. In other animals, respiratory variation in systemic venous return was prevented during cardiac tamponade, and the effects of this maneuver on respiratory variation in aortic pressure were observed. Failure of pulsus paradoxus to appear with cardiac tamponade under these circumstances would oppose the concept that increased pulmonary venous pooling with inspiration is the essential mechanism that decreases inspiratory filling of the left heart.

Methods

All the dogs were prepared by thoracotomy under pentobarbital anesthesia. All except six dogs in group D (*vide infra*) were studied after their chests had been closed and they had resumed spontaneous breathing. Pericardial and pleural pressures were measured through plastic catheters. A second plastic catheter in the pericardial space was used for injection of physiologic saline solution to induce cardiac tamponade. Pressures

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were measured with Statham P23Db and P23Bb and Sanborn 267B and 268B gauges on a multichannel Sanborn [1] or Electronics for Medicine [2] recorder. Flows were recorded by a Carolina Electronics [3] square wave electromagnetic flowmeter. Details of these methods have been published (1, 2).

Cardiac rhythm was monitored electrocardiographically in each animal, except where the electromagnetic flowmeter was in use. (The electric field from the electromagnetic flowmeter interfered with the electrocardiogram.) Data from dogs that developed arrhythmia were rejected. In several of the dogs in which no cardiac bypass had been instituted, transpericardial pressure was measured with a Sanborn 268B or a Statham differential transducer connected to the pleural and pericardial cavities.

A) Vena caval flow. In six dogs superior vena caval flow was measured before, during, and after acute cardiac tamponade. Simultaneous pressures were recorded from the pericardial and pleural spaces. In another six dogs an identical experiment was performed, except that inferior vena caval flow was recorded together with pressure from the inferior vena cava, the aorta, and the pleural and pericardial spaces. The magnetic probe of the flowmeter was placed so that it surrounded the superior or inferior vena cava approximately ½ cm away from the heart. The probe circumference was 1 to 5 mm less than the length of a silk thread that would just perceptibly compress the vena cava. The probes were calibrated by the injection of known volumes of blood

[1] Sanborn Co., Waltham, Mass.

[2] Electronics for Medicine, White Plains, N. Y.

[3] Carolina Medical Electronics, Winston-Salem, N. C.

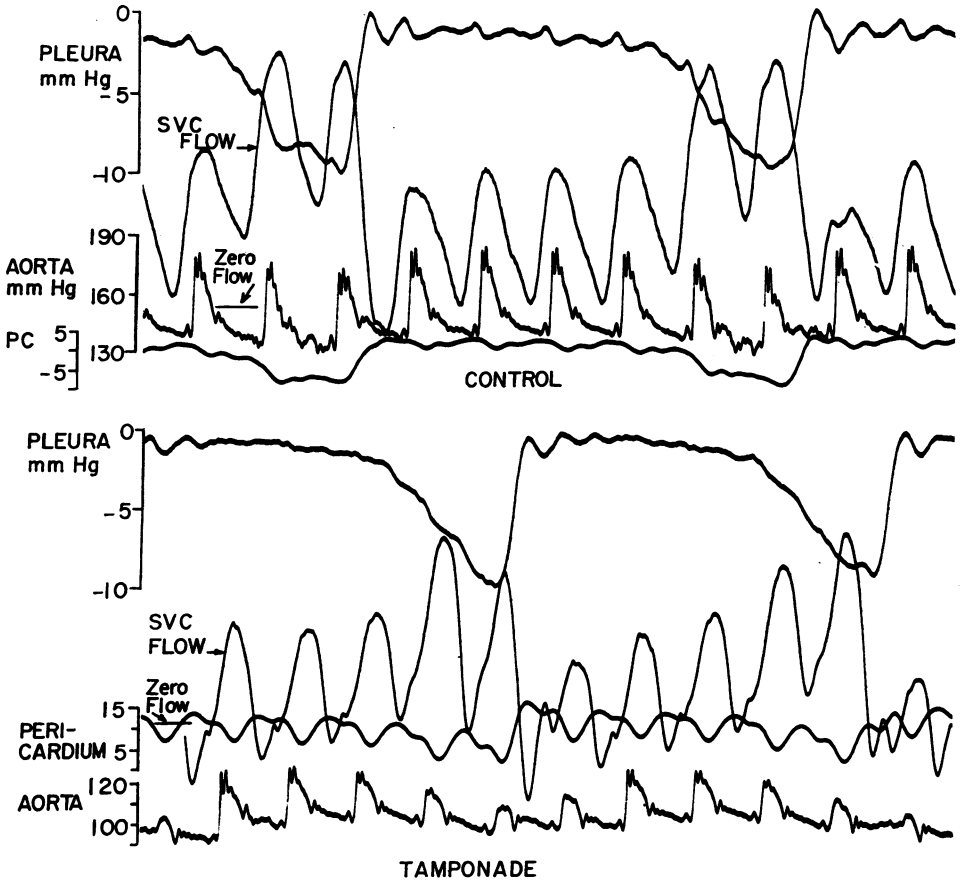

FIG. 1. THE EFFECT OF INSPIRATION ON SUPERIOR VENA CAVAL (SVC) FLOW. Above, control; below, during acute cardiac tamponade; PC = pericardium. Pressures are relative to atmosphere. Paper speed is 75 mm per second. During tamponade, pulsus paradoxus is present in the aortic pressure record. Superior vena caval flow is increased approximately twofold during inspiration in the control state and almost as much in the tamponade state. Intrapericardial and intrapleural pressures each decline approximately 9 mm Hg during inspiration in the control, but during tamponade pericardial pressure declines 5 mm Hg when intrapleural pressure falls 8 mm Hg.

TABLE I

Effect of respiration on vena

		Control							
		Expiration			Inspiration				
	Dog no.	Aortic pressure	Pleural pressure	Pericardial pressure	Aortic pressure	Inspiratory decline in systolic pressure	Pleural pressure	Pericardial pressure	Per cent flow increase
		mm Hg	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	
Superior caval flow:									
	1	130/75	−2.5	−0.5	120/75	10	−10	−7.5	25
	2	120/80	−3	−4	117/75	3	−7.5	−4	62
	3	150/110	−3.5	0	145/55	5	−13	−5	70
	4	160/110	−4.5	2	155/105	5	−7	−2	61
	5	120/105	−7.5	−5	117/104	3	−12	−11	28
	6	180/123	−3	−2	176/124	4	−6	−5	122
	Mean		−4			5	−9.25		61.3
	p value*								$p < 0.01$
Inferior caval flow:									
	7	155/110	−2.5	−2	145/105	10	−13	−11	20
	8	130/96	−2.5	−2	128/90	2	−5	−2	50
	9	120/95	−1	−4	113/90	7	−9	−4	28
	10	165/110	−2	−1	161/111	4	−6	−5	60
	11	185/127	−2.5	−2.5	181/127	4	−5.5	−5	77
	12	220/175	−2.5	−4	218/174	2	−5	−6	80
	Mean		−2.16			4.8	−7.25		52.5
	p value*								$p < 0.01$

* *t* test of statistical significance.

through vessels fitted through them. The height of the deflections was found to be proportional to the velocity of flow, and the area under the deflection was proportional to volume flow. We found such calibration to be valid only when carried out *in situ* after the animals had been sacrificed with the probe in precisely the same anatomic relation to the vessel as during the flow measurements. The limited space available in the venae cavae precluded setting up such an *in situ* calibration system without disturbing the position of the probe. Hence, in all experiments reported in this study only aortic flow was measured in milliliters per beat; flow changes in the venae cavae and the pulmonary artery were expressed as percentage deviations from the control. After each experiment, the zero level for the flowmeter was obtained without altering its position by producing temporary cardiac arrest with the intravenous injection of 30 to 50 mg acetylcholine.

B) Bypass experiments. In nine dogs the right heart was bypassed by draining superior and inferior vena caval blood into a dependent reservoir and pumping it from there at constant rate into the pulmonary artery. The azygos vein was ligated. The coronary sinus blood was not diverted. Pressures were measured in the aorta and in the pleural and pericardial spaces before, during, and after the induction of acute cardiac tamponade by increasing pericardial pressure 8 to 32 mm Hg above control. These pressures previously produced pulsus paradoxus in animals without cardiac bypass studied in our laboratory (1–3). Studies were made at flow rates from 30 to 188 ml per kg per minute in closed-chest animals that had resumed spontaneous respiration.

In another group of nine animals, respiratory variation in right heart filling was prevented by holding systemic venous return constant. The superior and inferior venae cavae, but not the coronary sinus, were drained into an open dependent reservoir, and the blood was pumped at constant rate into the right atrium through a Tygon R tube in the inferior vena cava. Studies were made as above in closed-chest animals at flow rates of from 35 to 200 ml per kg per minute.

C) Transpericardial pressure. Transpericardial pressure was measured by a Sanborn 268B differential pressure transducer or a Statham P23H transducer connected between the pericardial and pleural cavities. Differential pressures were recorded before, during, and after cardiac tamponade. The measurements were made in seven dogs during shallow and deep respiration.

D) Simulation of the effect of inspiration on systemic venous return. Three of these experiments were performed on closed-chest dogs, and six dogs were studied with open chests. The experiments were carried out during a brief period of apnea. The dogs in this group were prepared as those in group B were. The superior and inferior vena caval drainage was pumped at constant rate into the right atrium. Pressures were recorded from

TABLE I

caval flow during cardiac tamponade

Cardiac tamponade							
Expiration			Inspiration				
Aortic pressure	Pleural pressure	Pericardial pressure	Aortic pressure	Inspiratory decline in systolic pressure	Pleural pressure	Pericardial pressure	Per cent flow increase
mm Hg	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	
100/75	−2.5	5	82/72	18	−6.5	−2	22
75/55	−3	7	64/54	11	−7.5	7	22
125/95	−5	10	108/96	17	−15	7	82
87/73	−3	13	82/73	5	−6	11	5
55/49	−6.5	12	51/47	4	−11	7	32
105/94	−3	6	94/89	11	−6	3	121
	−3.83			10.8	−8.67		47.3
					$p < 0.05$ (vs. control)		$p < 0.05$
120/105	−2	4	95/82	25	−11	0	44
70/56	−2	10	60/53	10	−6	10	48
67/54	−1	12	57/52	10	−9	12	60
75/64	−2	16	66/62	9	−5	12	61
103/84	−2.5	8	90/81	13	−5	5.5	66
157/130	−1	4	136/122	21	−6	3	91
	−1.75			14.7	−7		61.7
				$p < 0.02$ (vs. control)			$p < 0.001$

the aorta and pulmonary artery and from the pericardial space. In the closed-chest dogs pressures were also recorded from the pleural space and were required to be subatmospheric and constant. In six dogs both sides of the chest were opened, and the flowmeter probe was placed around the descending aorta. The chests were not closed. In each of the nine dogs, during a period of apnea, 15 to 30 ml of blood was added over a second or two to the right atrial flow by opening a second line from the pump, which approximately doubled the flow rate. This procedure added approximately 5 ml per cardiac cycle for three or four cycles to systemic venous return, a value similar to the inspiratory increment of right ventricular stroke volume found in acute cardiac tamponade in dogs studied previously in this laboratory. The effect of this increment in right atrial inflow on pulmonary arterial pressure and aortic pressure and flow was observed and was compared with the effect of normal inspiration. Observations were made with and without tamponade and at several flow rates, as in the previously described animals.

E) Pulmonary arterial flow. In a separate group of six dogs the effect of inspiration on pulmonary arterial flow with and without cardiac tamponade was measured. The probe of our flowmeter was too large to permit closure of the pericardium with the probe around the main pulmonary artery. A smaller probe, chosen so as to constrict the vessel slightly, was therefore placed around the artery to the right lower lobe. Phasic flow records were obtained in the control state and at several levels of cardiac compression. The respiratory variation in flow through the lower lobar branch of the right pulmonary artery was assumed to be representative of that in the main pulmonary artery and was determined by comparison of the planimetrically integrated area under the stroke flow curves.

Results

Group A: vena caval flow. Our results confirm that, in anesthetized dogs without cardiac tamponade, quiet spontaneous inspiration produces a significant increase of superior and inferior vena caval blood flow (12), as shown in Table I. In each of the twelve dogs studied during cardiac tamponade inspiration was accompanied by a pronounced increase in vena caval flow. Since the flowmeter could not be calibrated *in situ,* changes in caval flow are expressed as a percentage of deviation from the control. Superior caval flow increased significantly an average of 61.3% in the control period and 47.3% during cardiac tamponade (Table I). Inferior caval flow increased significantly by an average of 52.5% in control

animals and by 61.7% during cardiac tamponade (Table I). There was no appreciable change in heart rate. Figures 1 and 2 illustrate examples of inspiratory acceleration of superior and inferior vena caval flow in the control and tamponade states. During expiration a small portion of the flow in the venae cavae was away from the heart in both the control and tamponade states. With cardiac tamponade, during the ensuing resting phase of respiration, as shown in Figures 1 and 2, caval flow gradually increased, presumably as the great veins gradually refilled after the increased emptying produced by previous inspiration.

In these twelve dogs, aortic systolic pressure fell 2 to 10 mm Hg during inspiration in the control period. Aortic systolic pressure fell 4 to 25 mm Hg during inspiration (pulsus paradoxus) when the intrapericardial pressure was elevated 5.5 to 17 mm Hg above control by injecting saline into the pericardial sac. In two animals, no. 4 and 5, in which blood pressures were considerably lowered by cardiac tamponade, pulsus paradoxus did not

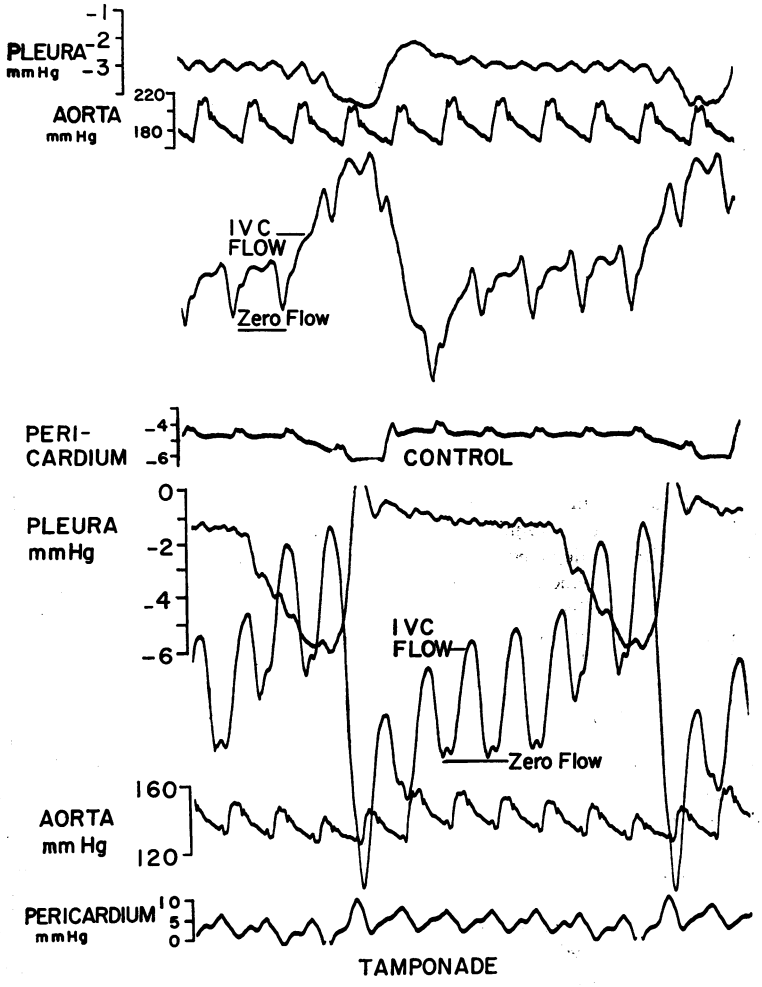

FIG. 2. THE EFFECT OF INSPIRATION ON INFERIOR VENA CAVAL (IVC) FLOW. Above, control; below, tamponade. Paper speed is 75 mm per second. Pressures are relative to atmosphere. During tamponade pulsus paradoxus is present in the aortic pressure record. Inferior vena caval flow is approximately doubled during inspiration in the control and tamponade states. During inspiration intrapericardial pressure declines 2 mm Hg, whereas intrapleural pressure declines 5 mm Hg. Net intrapericardial pressure is increased by inspiration.

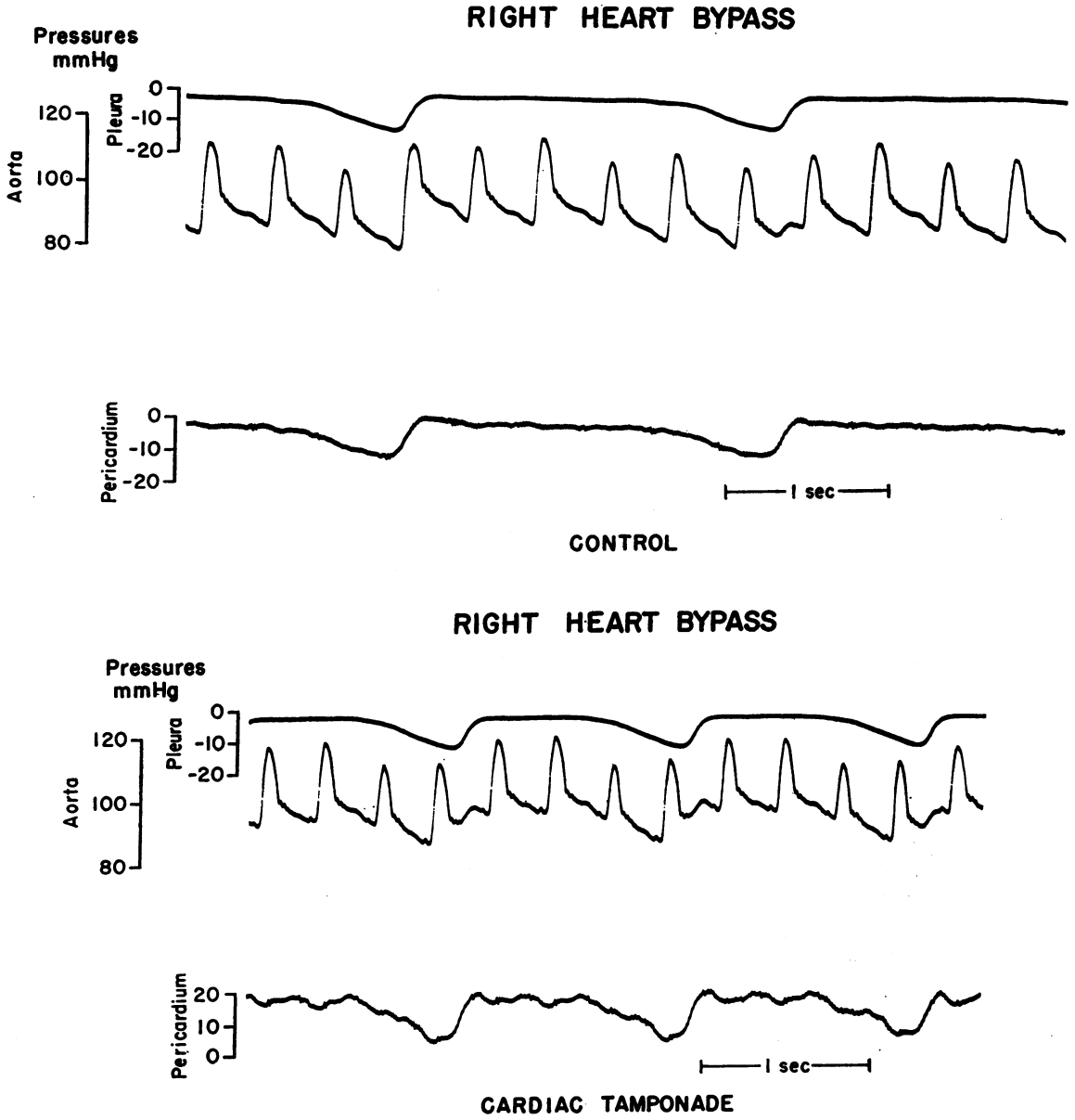

FIG. 3. THE EFFECT OF ACUTE CARDIAC TAMPONADE ON AORTIC PRESSURE DURING RIGHT HEART BYPASS. In the control, with inspiration intrapleural pressure falls 8 mm Hg, and aortic systolic blood pressure falls 9 mm Hg from the values in the resting phase of breathing. During tamponade, intrapericardial pressure has been raised 20 mm Hg. With inspiration intrapleural pressure declines 7 mm Hg, and aortic systolic pressures fall 8 mm Hg. The inspiratory fall of intrapericardial pressure equals or exceeds that in the pleural space.

develop. We have reported that excessive lowering of the blood pressure in experimental cardiac tamponade is often not associated with appreciable pulsus paradoxus (2). Although qualitative respiratory variations in venous return to the right heart may persist during severe cardiac tamponade, the quantitative variations in right heart filling, which can be induced thereby, must be greatly reduced. Animal no. 4 showed relatively little inspiratory increase of superior caval flow during tamponade.

Group B: bypass experiments. When superior and inferior vena caval flows were diverted from the right heart and pumped at constant rate into

TABLE II

Cardiac tamponade during constant

Dog no.	Flow	Control: Pleural pressure* Exp	Pleural pressure* Insp	Pleural pressure* Insp decline	Aortic pressure Exp	Aortic pressure Insp	Insp decline systolic pressure	Peri-cardial pressure†
	ml/kg/minute		*mm Hg*			*mm Hg*		*mm Hg*
277	62	−7	−12	5	103/ 75	100/ 70	3	−5
281	100	−3	− 8	5	149/ 89	145/ 84	4	−2
283	30	−9	−12	3	100/ 61	94/ 58	6	−6
	110	−9	−13	4	135/ 80	130/ 75	5	−7
	200	−9	−13	4	205/113	200/106	5	−7
284		−2	− 7	5	125/ 95	122/ 94	3	−3
287	55	−3	− 7	4	103/ 70	99/ 66	4	−2
	105	−2.5	− 7	4.5	150/ 95	145/ 93	5	−2
	160	−2	− 7	5	183/105	177/100	6	−2.5
288	60	−2	− 7	5	110/ 80	106/ 76	4	0
	90	−2	− 7	5	125/ 84	120/ 85	5	0
	160	−2	− 8	6	178/116	170/112	8	0
289		−4.5	− 6.5	2	110/ 74	105/ 72	5	−7
	48	−4.5	− 7.5	3	117/ 85	114/ 83	3	−2.5
	75	−2.5	− 7.5	5	110/ 80	110/ 80	0	−3
290	35	−1	− 5	4	90/ 83	86/ 79	4	−2
	107	−1	− 4	3	120/ 94	117/ 95	3	−2.5
317	50	−5	−12	7	109/ 83	105/ 80	4	−3
	105	−5	−10	5	130/ 94	126/ 90	4	−3
	172	−4	− 9	5	193/131	189/126	4	−2
Mean		−4.0	− 8.48	4.48			4.25	
p value (vs. control)‡								

* Exp = expiratory; insp = inspiratory.
† Pericardial pressures are averaged over the entire respiratory cycle.
‡ *t* test of statistical significance.

the pulmonary artery, elevations of intrapericardial pressure 10 to 25 mm Hg above control values consistently failed to cause pulsus paradoxus in the nine animals of this group (Figure 3) at all flow rates. Inspiratory fall in aortic systolic pressure averaged 4.2 mm Hg in control animals and 3.8 mm Hg during cardiac tamponade. During tamponade, aortic systolic pressure during both expiration and inspiration was usually the same or a few millimeters Hg higher than in the control period. Of the 16 experiments performed upon the nine animals in this group, in only two was the aortic systolic pressure significantly lower during cardiac tamponade. The depth of respiration, judged from the inspiratory level of intrapleural pressure, was essentially the same in the control period and during tamponade. Mean expiratory intrapleural pressure was − 3.6 mm Hg during control and − 3.7 mm Hg during tamponade. Mean inspiratory intrapleural pressure was − 8.2 mm Hg during control and − 8.6 mm Hg during tamponade. Although intrapleural pressures were excessively negative in some experiments, they were normal in four animals of this group.

When venous return to the right atrium was held constant throughout the respiratory cycle, pulsus paradoxus could not be produced by injecting saline into the pericardial space (Table II, Figure 4). This held true for pericardial pressure elevations from 8 mm Hg to 32 mm Hg and for all flow rates. Inspiratory decline of aortic systolic pressure averaged 4.25 mm Hg in the control period and 4.05 mm Hg during cardiac tamponade (Table II). Although pressures were excessively negative in some instances, they were normal in others—no. 284, 287, 288, 289, and 290 in Table II. As judged from inspiratory decline of intrapleural pressure, respiration was significantly more shallow during cardiac tamponade than during the control period. However, in 11 of 20 experiments the decline of intrapleural pressure during tamponade was equal to or greater than that during the control period (Table II). In only two of these eleven experiments did aortic

TABLE II

venous return to right atrium

Tamponade						
Pleural pressure			Aortic pressure			
Exp	Insp	Insp decline	Exp	Insp	Insp decline systolic pressure	Pericardial pressure†
	mm Hg			*mm Hg*		*mm Hg*
−7	−12	5	108/ 77	105/ 72	3	5
−3	− 7	4	147/ 89	143/ 87	4	12
−9	−12	3	120/ 79	115/ 75	5	18
−8	−12	4	100/ 75	95/ 70	5	25
−9	−13	4	205/113	201/105	4	20
0	− 4	4	120/ 95	119/ 93	1	10
−3	− 6	3	105/ 75	99/ 71	6	12
−2	− 5	3	150/ 95	145/ 90	5	10
−2	− 7	5	188/106	182/101	6	13.5
−2	− 8	6	110/ 80	105/ 75	5	13
−2	− 7	5	120/ 80	115/ 75	5	10
−2	− 7	5	175/115	164/110	11	16
−4	− 6.5	2.5	82/ 61	80/ 60	2	6
−5	− 7	2	85/ 55	82/ 53	3	15
−2	− 5	3	90/ 70	87/ 70	3	21
−1	− 5	4	90/ 84	85/ 78	5	6
−1	− 3	2	86/ 70	85/ 68	1	12
−4	− 9	5	110/ 80	108/ 79	2	20
−5	−10	5	130/ 95	126/ 92	4	17
−4	−10	6	201/132	200/127	1	16
−3.75	− 7.77	4.03			4.05	
$p > 0.05$	$p < 0.02$	$p < 0.05$				

systolic pressure decrease more with inspiration during cardiac tamponade.

Group C: transpericardial pressure. In control dogs with normal intrapericardial pressures and normal respiratory variation in venous return to the right heart, transpericardial pressure showed little or no rise during inspiration, as shown in Table III and Figures 1, 2, and 5. When respiratory variation in systemic venous return was prevented, transpericardial pressure likewise remained relatively constant throughout the respiratory cycle, whether or not cardiac tamponade was present (Table III, Figures 3 and 4).

Table III also compares the inspiratory decline of intrapericardial pressure with that in intrapleural pressure in animals with constant venous return to the right atrium or to the pulmonary artery. This Table does not contain all the experiments previously described or shown in Table II because in many studies the pericardial pressure was recorded as an electrical average and could not be used to follow respiratory fluctuations.

Section A in Table III shows that with constant venous return to the right atrium, pericardial pressure during cardiac tamponade fell as much with inspiration as did intrapleural pressure in 11 of 12 experiments. Thus transpericardial pressure rose during inspiration in only one experiment. Table III, section B demonstrates that with right heart bypass and constant blood flow to the pulmonary artery, during cardiac tamponade pericardial pressure fell as much (within 0.5 mm Hg) as intrapleural pressure in six of ten experiments. In only one experiment (animal no. 313) was there a considerable inspiratory rise in transpericardial pressure. This was associated with a considerable drop of intrapleural pressure. In control experiments we have found that an exaggerated inspiratory fall of intrapleural pressure is at times not completely reflected in the intrapericardial pressure. When respiratory variation in venous return to the right heart was present and cardiac tamponade had been produced, inspiration was accompanied by an increase in transpericardial pres-

TABLE III

Respiratory variations in pericardial

	Dog no.	Control								
			Expiration			Inspiration				
		Vena caval flow	Pleural pressure	Trans-pericardial pressure	Aortic pressure	Pleural pressure	Trans-pericardial pressure	Aortic pressure	Inspiratory change in trans-pericardial pressure	Inspiratory decline in aortic systolic pressure
		ml/kg/minute	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*
A) Constant right atrial return	277	62	−7	+4	103/ 75	−12	+4	100/ 70	0	3
	281	100	−3	+2	149/ 80	−8	+2	145/ 84	0	4
	283	30	−9	+5	100/ 61	−12	+4	94/ 58	−1	6
		110	−9	+5	135/ 80	−13	+5	130/ 75	0	5
		200	−9	+5	205/113	−13	+5	200/106	0	5
	284		−4.5	+7	125/ 95	−7.5	+5.5	122/ 94	−1.5	3
	287	55	−3	+2	103/ 70	−7	+3	99/ 66	+1	4
		105	−2.5	+0.5	150/ 95	−7	−1	145/ 93	−1.5	5
		160	−2	+1	183/105	−7	+2	177/100	+1	6
	288	90	−2	+5.5	125/ 84	−7	+5	120/ 85	−0.5	5
	289	75	−2.5	+0.5	110/ 80	−7.5	0	110/ 80	−0.5	0
	290	107	−1	+0.5	120/ 94	−4	−0.5	117/ 95	−1	3
	Mean		−4.5			−8.8			−0.5	3.8
B) Constant return to pulmonary artery	264	85*	−5	+1	155/120	−7.5	+0.5	153/120	−0.5	2
		110	−5	+5	163/110	−11	+3.5	158/107	−1.5	5
		170	−4.5	+4.5	215/145	−11	+4	206/140	−0.5	9
	265	30	−1	0	90/ 61	−6	+1	85/ 58	+1	5
		170	−3	+1	174/104	−10	+5	170/100	+4	4
	268	43	−5	0	130/ 81	−9	0	128/ 79	0	2
		100	−7.5	+2	110/ 60	−11	+3	106/ 58	+1	4
	313	32	−2	+2	90/ 71	−6.5	−0.5	87/ 69	−2.5	3
		94	−2	+2	132/ 94	−6.5	−0.5	128/ 90	−2.5	4
	314	105	−5	0	138/100	−9.5	+0.5	132/ 97	+0.5	6
	Mean		−4.0			−8.8			−0.1	4.4
C) Uncontrolled venous return	19		−4.5	0	165/130	−7	0	158/128	0	7
	20		−3	+1	138/ 64	−9	+2	129/ 60	+1	9
	21		−4.5	+1.5	125/100	−8	+4	121/ 96	+2.5	4
	22		−2	0	155/102	−7	+1.5	150/101	+1.5	5
	23		−4	0	153/117	−10	0	148/117	0	5
	24		−3.5	0	150/105	−12	+2	145/100	+2	5
	25		−3	−2	134/ 80	−7	−1	130/ 78	+1	4
	Mean		−3.2			−8.6			+1.1	5.6
	p value†									

* Values in group B represent pulmonary arterial flow.
† *t* test of statistical significance.

sure (Table III, section C, Figures 1, 2, and 5). As shown in section C of Table III, during tamponade the mean inspiratory transpericardial pressure of 13.2 mm Hg was significantly greater than the pressure of 8.7 mm Hg during expiration, $p < 0.001$. The inspiratory rise of transpericardial pressure was significantly greater during tamponade than during the control period, $p < 0.001$. In this group, there was a significant paradoxical pulse as shown by the greater inspiratory decline of aortic systolic pressure, $p < 0.01$. As judged by the inspiratory and expiratory values for intrapleural pressure, the depth of respiration was not significantly greater during tamponade than during the control period.

Group D: simulation of the effect of inspiration

TABLE III

pressure during cardiac tamponade

Tamponade							
Expiration			Inspiration				
Pleural pressure	Trans-peri-cardial pressure	Aortic pressure	Pleural pressure	Trans-peri-cardial pressure	Aortic pressure	Inspiratory change in trans-peri-cardial pressure	Inspiratory decline in aortic systolic pressure
mm Hg	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*
−7	+14	108/ 77	−12	+14	105/ 72	0	3
−3	+18	147/ 89	−7	+18	143/ 87	0	4
−9	+36	120/ 79	−12	+35	115/ 75	−1	5
−8	+45.5	100/ 75	−12	+44.5	95/ 70	−1	5
−9	+44	205/113	−13	+43	201/105	−1	4
−3.5	+17.5	120/ 95	−5	+16	119/ 93	−1.5	1
−3	+18.5	105/ 75	−6	+18.5	99/ 71	0	6
−2	+13	150/ 95	−5	+12	145/ 90	−1	5
−2	+19	188/106	−7	+19	182/101	0	6
−2	+24	120/ 80	−7	+24	115/ 75	0	5
−2	+24	90/ 70	−5	+25	87/ 70	+1	3
−1	+15	86/ 70	−3	+14.5	85/ 68	−0.5	1
−4.3	+24		−7.8	+23.6		−0.4	4.0
−5	+16	165/122	−7.5	+17.5	163/120	+1.5	2
−5	+15	165/108	−11	+13.5	161/107	−1.5	4
−3.5	+10.5	225/150	−10	+11	219/146	+0.5	6
−1	+17	90/ 60	−7	+19	85/ 60	+2	5
−4	+28	180/105	−11	+30	174/101	+2	6
−3	+11	140/100	−7.5	+11.5	138/ 99	+0.5	2
−5.5	+20.5	125/80	−9	+21	123/ 78	−0.5	2
−2	+14	91/ 70	−11.5	+18.5	86/ 68	+4.5	5
−2	+13	140/ 96	−7	+13	135/ 92	0	5
−5	+21	132/ 98	−9.5	+16.5	127/ 97	−4.5	5
−3.6	+16.6		−9.1	+17.2		+0.5	4.2
−3.5	+8	81/ 62	−8	+12	63/ 49	+4	18
−3.5	+6	87/ 63	−10.5	+12.5	75/ 56	+6.5	12
−4	+14	39/ 25	−12	+18.5	31/ 23	+4.5	8
−1.5	+14	124/105	−5	+19	110/104	+5	14
−5	+5	135/110	−10.5	+8.5	115/110	+3.5	20
−3	+4	91/ 78	−12	+8	80/ 74	+4	11
−3	+10	87/ 64	−8	+14	75/ 60	+4	12
−3.4	+8.7		−9.4	+13.2		+4.5	13.6
$p > 0.6$ (vs. control)			$p > 0.2$ (vs. control)	$p < 0.001$ (vs. expiration)		$p < 0.001$ (vs. control)	$p < 0.01$ (vs. control)

on systemic venous return. Of the nine animals studied, aortic stroke flow was measured in six. In the control period, when venous return to the right heart was increased by 15 to 30 ml during suspended respiration, pulmonary arterial systolic pressure rose 4 to 10 mm Hg, aortic systolic pressure fell 0 to 2 mm Hg, mean 0.55 mm Hg. An experiment from this group is illustrated in Figure 6. Aortic stroke flow change was from − 1 to + 2 ml, average + 0.3 ml. Intrapericardial pressure did not change when venous return was increased during the control period. During cardiac tamponade, pulmonary arterial systolic pressure rose 5 to 13 mm Hg immediately after increasing venous return to the right heart. Aortic systolic pressure at first fell 4 to 11 mm Hg, mean 6.66

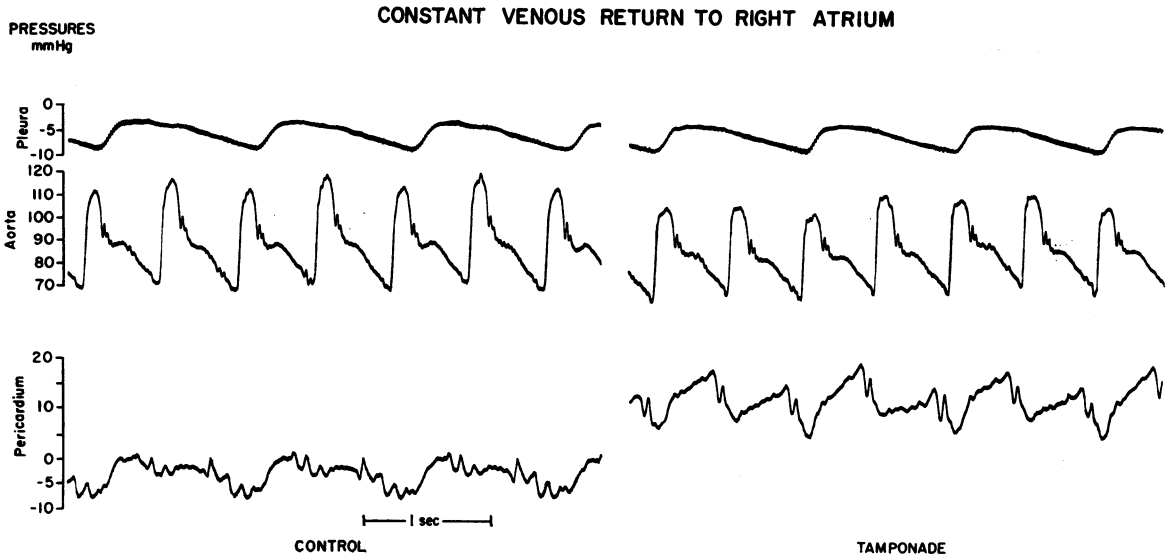

FIG. 4. THE EFFECT OF ACUTE CARDIAC TAMPONADE ON AORTIC PRESSURE WHEN SYSTEMIC VENOUS RETURN IS HELD CONSTANT. In the control, an intrapleural pressure fall of 4.5 mm Hg during inspiration is accompanied by a fall in systolic aortic pressure of 7 mm Hg. During tamponade, the pericardial pressure is elevated 14 mm Hg above control. During inspiration, intrapleural pressure falls 4.5 mm Hg, and aortic systolic pressure falls 8 mm Hg. Transmural pericardial pressure does not change with respiration. Blood flow is 48 ml per kg per minute.

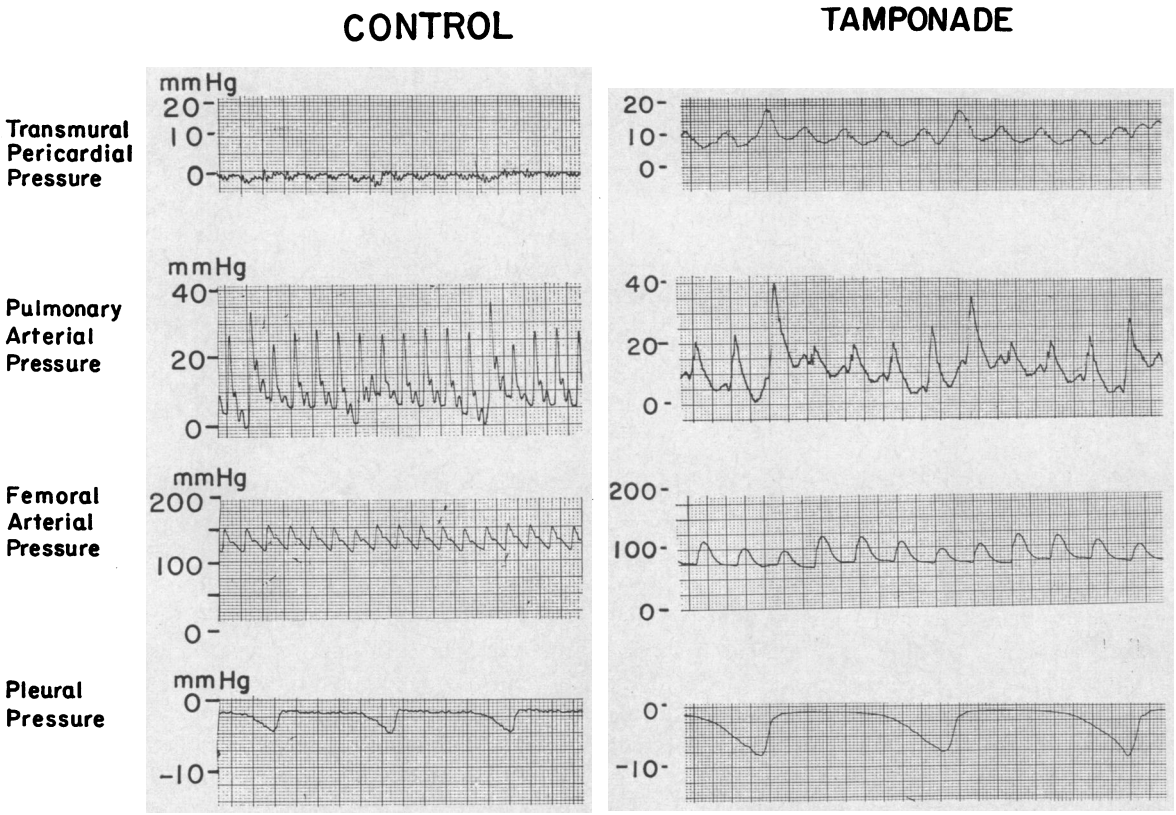

FIG. 5. EFFECT OF INSPIRATION ON TRANSMURAL PERICARDIAL PRESSURE IN CONTROL AND CARDIAC TAMPONADE. In the control period there is no significant respiratory change in transpericardial pressure. During tamponade, in inspiration there is a pronounced increase in transpericardial pressure. Inspiration is deeper during tamponade, but in controls intrapleural pressure decline of less than 10 mm Hg did not alter transpericardial pressure.

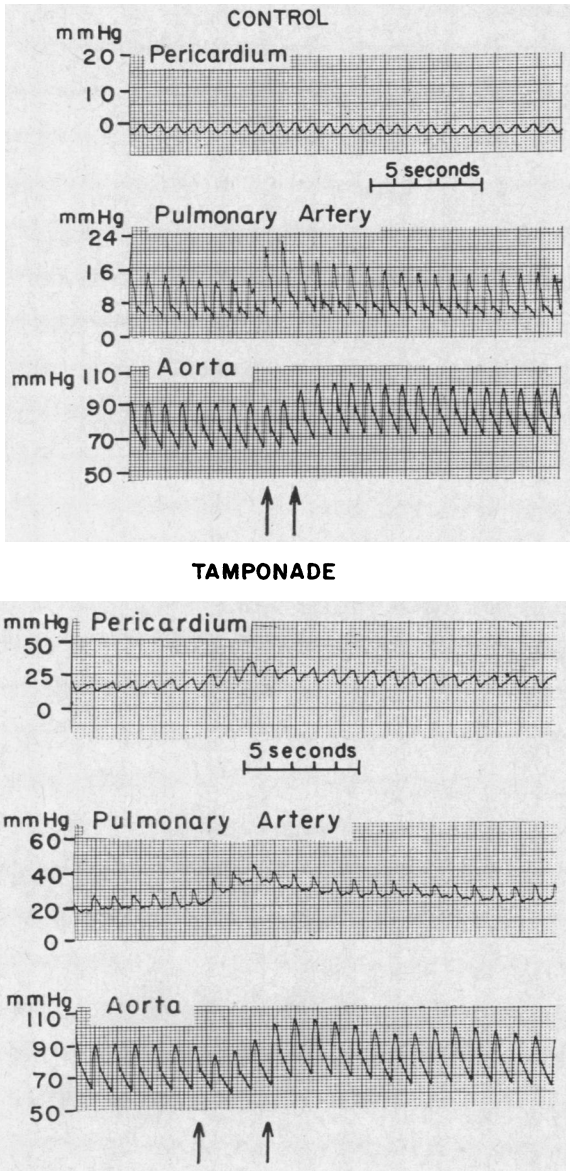

FIG. 6. THE EFFECT OF INCREASED VENOUS RETURN ON (A) CONTROL AND (B) TAMPONADE. *A*) The effect on pulmonary arterial and aortic pressures of an increase of approximately 15 ml in return to the right atrium during apnea after a period of steady controlled flow. Pulmonary arterial pressure rises promptly. There is no change in intrapericardial pressure. The aortic pressure rise is delayed for two cardiac cycles and is preceded by a small decline (1 mm Hg). The arrows indicate the period of the addition of blood to the right atrium.

B) The effect on pulmonary arterial and aortic pressures of an increase of approximately 15 ml in return to the right atrium during apnea after a period of steady controlled flow. The increased pulmonary arterial pressure is accompanied by a fall in aortic pressure of 7 mm Hg. Aortic pressure rise lags behind that in pulmonary arterial pressure by three cardiac cycles. The pericardial pressure is increased by the addition of blood to the right heart. The arrows indicate the period of the addition of blood to the right atrium.

mm Hg, $p < 0.001$ as compared to control. Aortic stroke flow decreased 3 to 9 ml, an average of 4.8 ml, $p < 0.02$ as compared to control. During tamponade, increased return to the right heart was followed by a rise of intrapericardial pressure of 2 to 10 mm Hg, mean 5.5 mm Hg. The heart rate did not change during these experiments. When premature cardiac contractions occurred, the experiments were discarded.

Group E: pulmonary arterial flow. Pulmonary arterial branch flow increased with inspiration during the control period and when intrapericardial pressure was progressively raised by the injection of saline into the pericardial sac (Figure 7, Table IV). In the control period the percentage increment of maximal inspiratory stroke flow over minimal expiratory stroke flow averaged 47%. During cardiac tamponade the inspiratory increase of branch stroke flow averaged 83.7%. The inspiratory increase of pulmonary arterial branch flow was significant both in the control period and during tamponade (Table IV). The largest pulmonary arterial stroke flow occurred at the end of inspiration when the aortic systolic and pulse pressures were minimal.

Discussion

In man, systemic systolic blood pressure normally declines a few millimeters Hg during inspiration. When, during quiet breathing, inspiratory pressures fall more than 6 to 8 mm Hg, pulsus paradoxus is probably present. In these experiments, anesthetized dogs demonstrated an inspiratory decrease in systolic blood pressure of 2 to 10 mm Hg. When, with an equal depth of respiration, cardiac tamponade was associated with a few millimeters Hg greater inspiratory fall of systolic blood pressure, pulsus paradoxus was considered to be present.

Five groups of observations from these studies are consistent with the hypothesis that the inspiratory decrease of left ventricular stroke output during cardiac tamponade depends upon an inspiratory increase of venous return to the right heart. First, systemic venous return was increased during inspiration even during severe cardiac tamponade. Second, there was no pulsus paradoxus during

cardiac tamponade when venous return to the right heart was constant or when the right heart was bypassed. Third, aortic pressure decreased during cardiac tamponade when there was a sudden increase in right heart filling. Fourth, transpericardial pressure rose with inspiration during cardiac tamponade. Fifth, in nearly all experiments when there was constant venous return to the right heart, cardiac tamponade did not prevent normal inspiratory fall of intrapericardial pressure. It is unlikely that an increase of intrapericardial pressure caused by diaphragmatic stretch is an essential mechanism in the production of pulsus paradoxus because transpericardial pressure did not change during respiration when systemic venous return was constant.

When low flow rates were employed to secure low fixed cardiac outputs in the experiments with controlled venous return, inspiratory increase in the capacity of the pulmonary vascular bed should not have been prevented, and yet acute tamponade did not cause pulsus paradoxus. These observations do not suggest that increased inspiratory pulmonary vascular pooling is the essential mechanism of pulsus paradoxus in acute cardiac tamponade. We have demonstrated that, when there

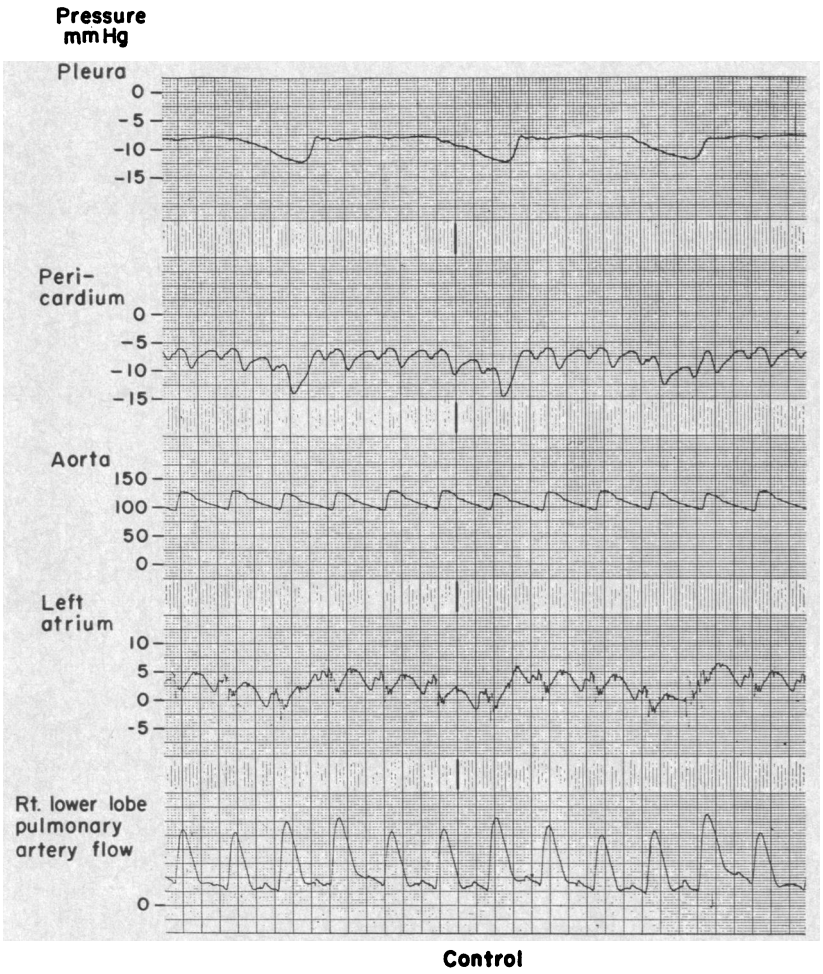

FIG. 7. THE EFFECT OF INSPIRATION ON FLOW THROUGH THE RIGHT LOWER LOBE BRANCH OF THE PULMONARY ARTERY IN CONTROL AND CARDIAC TAMPONADE. From above down: pleural pressure, pericardial pressure, aortic pressure, left atrial pressure, pulmonary arterial flow. Pericardial pressure is raised 14 mm Hg above control during tamponade. Pulmonary arterial branch flow is increased 37% during inspiration in control and 111% during tamponade.

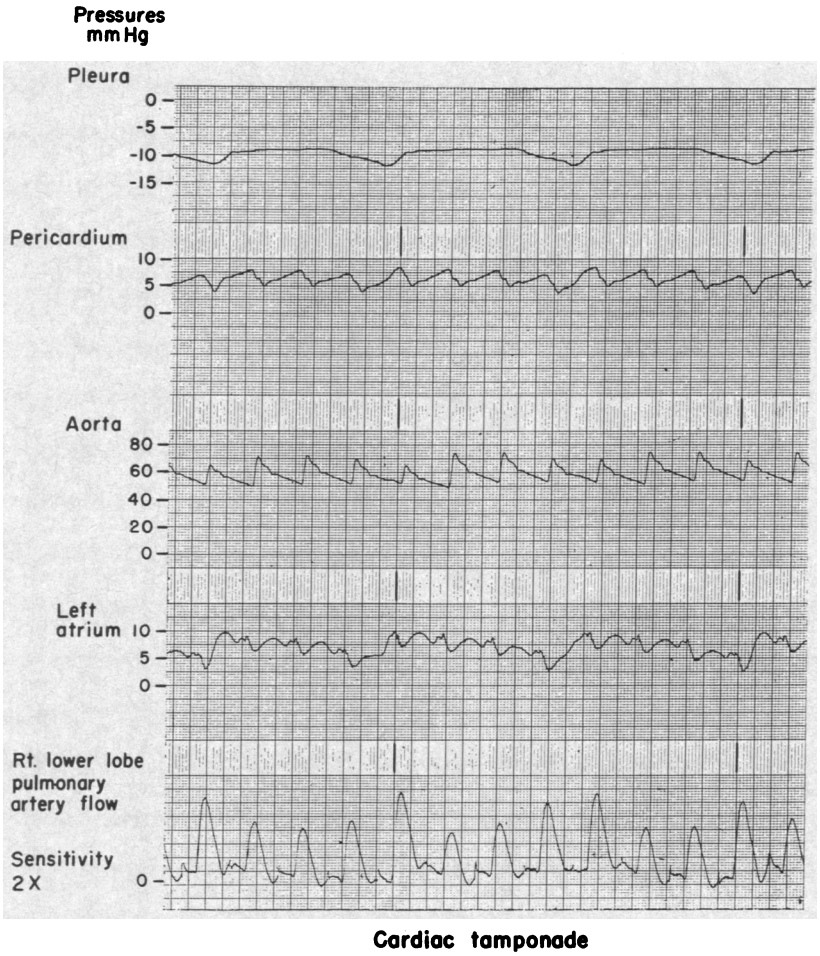

FIG. 7.—*Continued.*

is no inspiratory increase of blood flow to the right atrium, the pericardial pressure may fall normally with inspiration even during cardiac tamponade. Hence, diaphragmatic pericardial stretch and failure of transmission of negative intrathoracic pressure to the pericardium are not verified as mechanisms that impair inspiratory filling of the left heart.

These results support the ideas of Dornhorst, Howard, and Leathart (10), and Isaacs, Berglund, and Sarnoff (11), that the inspiratory expansion of right heart volume within a taut pericardium impedes filling of the left ventricle and is an important underlying mechanism of pulsus paradoxus in pericardial disease. We found that venous return to the right heart increased with inspiration in spite of cardiac tamponade and that when this increase was prevented, cardiac tamponade did not produce pulsus paradoxus. The inspiratory increase of pulmonary arterial stroke flow during cardiac tamponade demonstrated in these experiments supports the concept that the inspiratory increase of venous return is followed by increased right heart filling and then by increased right ventricular output. Increased inspiratory venous return to the right heart during tamponade was also suggested by the observations of Golinko, Kaplan, and Rudolph (7). These investigators, employing cineangiocardiography, found that iodinated oil droplets placed in the inferior vena cava of animals with experimental cardiac tamponade moved little during expiration but moved toward the right atrium in inspiration. It is unlikely that inspiratory increase in systemic venous return could be stored in the small segment of extrapericardial vena cava between the flow probe

TABLE IV

Right pulmonary arterial branch flow in cardiac tamponade

Dog no.	Control						Tamponade					
	Expiration		Inspiration				Expiration		Inspiration			
	Pleural pressure	Aortic pressure	Pleural pressure	Aortic pressure	Per cent increase in flow	Peri-cardial pressure	Pleural pressure	Aortic pressure	Pleural pressure	Aortic pressure	Per cent increase in flow	Peri-cardial pressure
	mm Hg	*mm Hg*	*mm Hg*	*mm Hg*		*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*		*mm Hg*
13	−11	142/ 95	−15	137/ 93	50	−12	−10	70/50	−12	62/48	213	+15
14	− 3	170/127	− 8.5	164/125	45	− 2.5	− 1	129/93	− 6	110/88	42	+10.5
15	− 2	120/ 83	− 7	114/ 81	46	− 2	− 2	81/59	− 7	74/58	60	+ 7
16	− 2		− 6		35	− 3	− 2		− 8		42	+ 4
17	− 3	157/102	− 8	153/100	37	− 3.5	− 3	100/83	− 8	91/80	31	+11.5
18	− 8	130/ 95	−12	125/ 96	66	−11.5	− 9	72/52	−12	65/50	114	+ 6
Mean					+47						+83.7	
p value*					$p < 0.001$						$p < 0.05$	

* *t* test of statistical significance.

and the heart. Therefore, the increased caval flow would expand right heart volume. Inspiratory increase in return to the right heart during tamponade was confirmed by our observations of increase in pulmonary arterial branch flow during inspiration. We also found that when right heart filling was augmented artificially during a period of apnea in acute cardiac tamponade, aortic pressure and flow were temporarily diminished and the pressure in the pericardial sac rose. This observation is the analog of the observed inspiratory decrease of left heart output during the period of increased right heart filling and output with cardiac tamponade. The number of cardiac cycles required for transmission of inspiratory increase of right ventricular output through the pulmonary circulation is consistent with the later expiratory rise of left ventricular output that occurs after two or three heart beats.

Normally there is less respiratory variation in aortic stroke flow than in pulmonary stroke flow. Guz and associates (13) placed flowmeters on the aorta and pulmonary artery of dogs and found a striking inspiratory increase in pulmonary arterial flow and small respiratory changes in aortic flow. Goldblatt, Harrison, Glik, and Braunwald (14) studied respiratory variations in left and right ventricular dimensions in man with metal clips that had been sewn on the ventricles at previous thoracotomy. They found that large inspiratory increases in right ventricular dimensions preceded small increases in left ventricular dimensions by one to three cardiac cycles. The data obtained from our experiments, in which a small volume of blood was added to the "normal" vena caval return to the right atrium, support the earlier concept (3) that in normal subjects a small inspiratory fall in aortic pressure for the most part represents a considerably decreased output from the right ventricle in the preceding expiration, damped in the capacitance vessels of the lung. This decline in aortic pressure and flow begins during the resting phase of respiration and extends into inspiration.

We propose that in cardiac tamponade the decline of systemic blood pressure from its expiratory peak results from a complex mechanism. During the quiet phase of respiration and before inspiration begins, the systemic pressure begins to fall. This decline results from decreased left heart

filling as the right heart output into the lungs wanes from the peak effect of the previous inspiration. As inspiration begins, further decline of systemic pressure results from the transmission of increasingly negative intrathoracic pressure. In later inspiration there is increased right heart filling, transpericardial pressure rises, and left heart filling is further impaired.

Our observations do not conflict with those of Golinko and associates (*7*), although the interpretations may differ. Golinko's studies showed that the movement of iodinated oil droplets from pulmonary vein to left atrium was greatly decreased or actually reversed during inspiration in experimental cardiac tamponade. The inspiratory rise of transmural pericardial pressure found in our studies would be expected to hinder the movement of blood from the extrapericardial pulmonary veins into the intrapericardial veins and left atrium. From our studies we believe that inspiratory increase of right heart output is essential to the inspiratory rise of pericardial pressure and also, by causing rhythmic variation in left ventricular filling, that it leads to the exaggerated inspiratory decline of left ventricular stroke output. Golinko and associates interpreted their observations to indicate that the greater inspiratory fall of pulmonary vein pressure than of left atrial pressure was the essential reason for the inspiratory decrease in left heart filling. We agree with this concept but would like to go one step further and say that this would not occur without respiratory fluctuation in right heart filling. With tamponade, during early inspiration, there is an absolute pressure drop in both right and left atria. Since pressure also drops in the pulmonary veins but rises in the extrathoracic systemic veins, right heart venous return rises, but left heart return from the pulmonary veins does not. As the right heart fills, the inspiratory intrapericardial pressure decline is reduced, and there is further difficulty in filling the left heart from the pulmonary veins. Hence, there is a normal degree of inspiratory pulmonary venous pooling in cardiac tamponade, which acts as a permissive mechanism: the exaggerated inspiratory difficulty in left heart filling is caused by the increased return to the right heart with the ensuing reduction of inspiratory fall of intrapericardial pressure.

Summary

1) During inspiration, venous return to the right heart increased both in normal dogs and in those with cardiac tamponade.

2) Transpericardial pressure rose during inspiration in dogs with cardiac tamponade but failed to rise in those with controlled constant venous return or in normal dogs.

3) Cardiac tamponade, with intrapericardial pressure increased by 6 mm Hg or more, consistently produced a paradoxical pulse in the aorta with an exaggerated inspiratory decline of left ventricular stroke output. Similar degrees of cardiac tamponade failed to produce a paradoxical pulse when the respiratory variation of venous return to the right heart was prevented.

4) In apneic animals, the hemodynamic effect of inspiration was simulated by suddenly increasing venous return to the right heart. This increment was immediately followed by a decrease in aortic pressure as left ventricular filling was reduced.

5) The normal slight inspiratory fall of left ventricular output reflects a delay in transmission through the pulmonary circulation of the expiratory fall of right ventricular output. With cardiac tamponade, inspiration increased right ventricular volume, raised transpericardial pressure, and reduced left ventricular filling. Thus, the normal inspiratory fall of left ventricular output was exaggerated.

6) Inspiratory stretching of the pericardium or abnormal inspiratory pooling of blood in the pulmonary vessels did not appear to be primary mechanisms in the production of a paradoxical pulse in these experiments.

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