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Vascular Waterfall Phenomenon in the Bovine[1] (38209)

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The "vascular waterfall" concept applies to those situations in the circulation wherein flow in a collapsible vessel is more importantly determined by altered transmural pressure owing to extravascular compression rather than by the longitudinal gradient (1–6). The vessel may be partially closed at a fixed cross-sectional area or, more commonly the area may vary with time (flutter). Downstream pressure does not influence blood flow until it exceeds the surrounding pressure. This mechanism undoubtedly accounts for decreased blood flow in the lung apex where alveolar pressure exceeds pulmonary capillary pressure and for collapse of veins at their entry into the thoracic cavity (7–12). During the course of hemodynamic studies on unanesthetized normal calves restrained on their side we have observed a pressure gradient between the abdominal and thoracic inferior vena cava (IVC) at the level of the diaphragm. In calves with elevated right atrial pressures due to Brisket Disease (BD) no gradient was present. An analysis of these experiments forms the basis for this report.

Methods. Thirty-two experiments were performed on 26 normal unanesthetized Hereford calves (average weight 103 kg) restrained on their side. The external jugular vein was surgically exposed under local lidocaine anesthesia. A number 8 Cournand catheter was introduced and under fluoroscopic guidance advanced to the abdominal IVC. This catheter was connected to a Statham P23Db pressure transducer. Heparin, 200 mg intravenously, was given to prevent formation of blood clots in the catheter. Pressure and the electrocardiogram were recorded on an oscillographic recorder (Minneapolis Honeywell, Denver, Colorado). By direct catheter withdrawal under fluoroscopy pressure was continuously recorded from the abdominal to the thoracic IVC and into the right atrium (RA). In 2 calves simultaneous pressures were recorded in the abdominal and thoracic IVC using 2 catheters.

In 5 normal calves the Cournand catheter was replaced by a catheter tip pressure transducer (Millar Instruments, Inc., Houston, Texas). Calibration was achieved using right ventricular pressure. The catheter was then positioned in the abdominal IVC. Pressure was recorded with the animal on its side and then while standing.

Seventeen experiments were performed on 17 calves with BD (average weight 122 kg) using identical methods. In 9 of the 17 calves with BD additional pressure measurements from above and below the diaphragm were made after phlebotomy. An average of 1850 ml of blood was taken from each calf over a 15 min period.

Results. In 32 experiments in 26 normal calves the abdominal and thoracic IVC pressures obtained by direct catheter withdrawal were 15 ± 0.9 and 2 ± 0.5 mm Hg, respectively (mean ± SE) with a pressure gradient of 13 ± 1 mm Hg (Fig. 1). A comparison of simultaneously recorded abdominal and thoracic IVC pressures is shown in Fig. 2 to illustrate the fall in IVC pressure to the RA level during withdrawal

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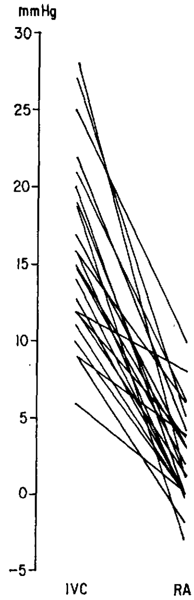

FIG. 1. Individual experiments showing mean pressure in the abdominal inferior vena cava (IVC) and right atrium (RA) obtained by catheter withdrawal. Change in pressure occurred at the diaphragm.

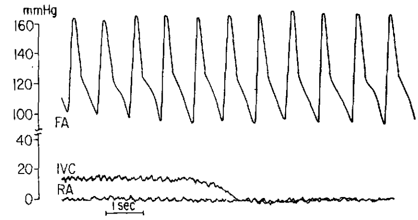

FIG. 2. Simultaneous measurement of femoral artery (FA) abdominal inferior vena cava (IVC) and right atrial (RA) pressures demonstrating the decrease in IVC pressure as the catheter is withdrawn past the diaphragm.

of the catheter past the diaphragm. Positive and negative variations in the thoracic IVC and RA pressures corresponding to the respiratory cycle were not observed in the abdominal IVC pressure. A comparison of pressures above and below the diaphragm recorded simultaneously and at increased sensitivity by two catheter tip pressure transducers is shown in Fig. 3. Pressure fluctuations in the abdominal IVC corresponding to the possible flutter motion of the vessel wall could not be detected in this recording.

In the 5 calves in which standing abdominal IVC pressure was compared to that obtained while lying on their side the pressures were 2 ± 1.7 and 16 ± 1.5 mm Hg, respectively (Fig. 4). Only one of the 5 calves had an elevated IVC pressure in the standing position.

In the 17 calves with BD restrained on their side the RA pressure was 36 ± 1.0 mm Hg without a gradient between the abdominal and thoracic IVC. In the 9 calves that underwent phlebotomy the RA pressure averaged 36 mm Hg before and 19 after phlebotomy. In 6 calves there was a corresponding reduction in abdominal IVC pressure; however, in 3 calves a gradient developed between the abdominal and thoracic IVC (Fig. 5).

Discussion. These experiments have demonstrated a posture related pressure gradient within the IVC of the calf. The vascular waterfall hypothesis may be invoked to explain these observations. With the calf on its side the intraabdominal pressure surrounding the IVC becomes greater than the distending pressure within the vessel. The vessel collapses resulting in progressive increase in pressure "upstream" in the abdominal vena cava. Eventually a positive transmural distending pressure is restored and the vessel expands. While flow was not measured in these experiments we predict that it would be more dependent upon the orifice size rather than the pressure gradient between the distal IVC and RA. With decompression of the upstream or abdominal vena cava, transmural pressure declines to the point of vessel collapse. This pattern recurs cyclically and gives rise to flutter. Our attempts to record pressure fluctuations in the abdominal IVC corresponding to flutter motion of the vessel wall in one experiment were unsuccessful, despite the use of pressure tip transducers positioned immediately above and below the diaphragm. The absence of a pressure gradient within the IVC of calves with increased RA pressure due to BD indicates that when intravascular pressure exceeds that surrounding the vessel collapse is prevented and the waterfall phenomenon inoperative. This emphasizes the

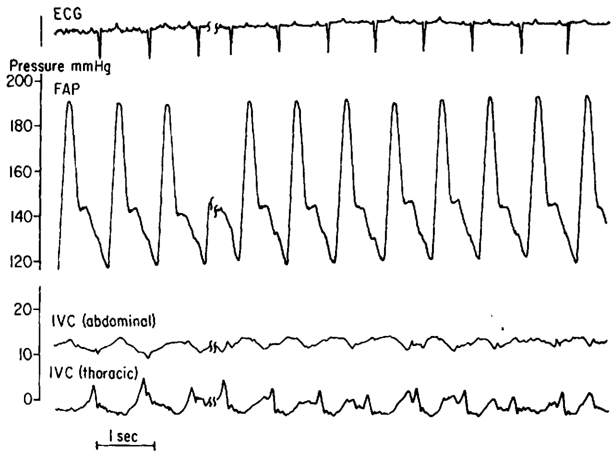

FIG. 3. Simultaneously recorded pressures using catheter tip pressure transducers located in the abdominal inferior vena cava (IVC) just below the diaphragm and in the thoracic IVC in a normal calf. Femoral artery pressure (FAP) shown for comparison.

fact that when downstream intravascular pressure exceeds extravascular pressure this phenomenon is obviated. The observation that phlebotomy may induce an abdominal to thoracic IVC gradient in some calves with BD adds further support to this thesis. The absence of a gradient in 6 calves is probably due to an insufficient decrease in RA pressure to allow the waterfall phenomenon to become operative.

As expected the fall in IVC pressure occurred precisely at the level of the diaphragm where there is an abrupt difference in transmural pressure along the course of the IVC when the calf is lying on its side.

The absence of the pressure gradient within the IVC in the standing position ostensibly reflects the superior (dorsal) position of the vessel relative to the abdominal contents.

In 5 normal calves RA pressures above 5 mm Hg were recorded. In 2 calves mild pulmonary hypertension (mean pulmonary artery pressure 25 mm Hg) existed at the time of RA pressure measurement. In the other 3 calves there was either marked bloating or struggling during the measurements.

The waterfall phenomenon offers a plausible explanation for an "old wives tale" widely known that cattle and sheep die when they accidentally become trapped in

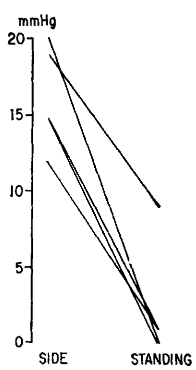

FIG. 4. Individual experiments showing mean pressure in the abdominal inferior vena cava with the animal in its side and while standing.

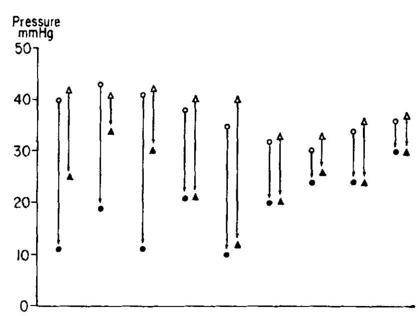

FIG. 5. Pressure in the right atrium (circles) and abdominal inferior vena cava (triangles) before phlebotomy (open symbols) and after phlebotomy (closed symbols) in each of 9 calves with brisket disease.

the supine posture. Also, calves are being used with increasing frequency in cardiopulmonary research, especially that related to circulatory and cardiac assist devices, and the effect of this phenomenon upon the dynamics of the peripheral circulation (especially renal) may be important. Finally, a comparable mechanism may be operative in some patients with tense ascites, obesity or during pregnancy (11).

Summary. In 32 hemodynamic studies on 26 unanesthetized normal calves (average weight 103 kg) lying restrained on their side abdominal inferior vena cava (IVC) and right atrial (RA) pressures obtained by catheter withdrawal under fluoroscopy were 15 ± 0.9 and 2 ± 0.5 mm Hg, respectively. The change in pressure occurred at the level of the diaphragm. Positive and negative variations in RA pressure corresponding to the respiratory cycle were not observed in the IVC pressure recorded below the diaphragm. In 5 calves IVC pressure was 2 ± 1.7 mm Hg standing and 16 ± 1.5 mm Hg while restrained on their side. In 17 calves with Brisket disease (BD) restrained on their side RA pressure was 36 ± 2.0 mm Hg without an IVC to RA gradient. The data suggest that significant narrowing of the IVC occurs at the level of the diaphragm in normal calves lying on their side presumably related to the effect of the weight of the abdominal contents on the IVC transmural pressure. The absence of an ICV to RA pressure gradient in calves with elevated RA pressure due to BD emphasizes the important role of outflow pressure in the vascular waterfall phenomenon.

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