Relationship Between Tracheal Air Flow and Induced Changes in Intrathoracic Volume

A Basis for Calibration of Pneumocardiogram

Jerry L. WESSALE, Ph.D., Joe D. BOURLAND, E.E., Ph.D.,
and Leslie A. GEDDES, M.E., Ph.D., F.A.C.C.

SUMMARY

The volume of air moved into the trachea due to ventricular activity—a record of which is the pneumocardiogram (PNCG)—is always less than true stroke volume. A new method of investigating this relationship consists of inducing a known volume change (ΔV_{in}) within the thorax and measuring the volume of air (ΔV_{out}) recorded with a pneumotachograph connected to the trachea. The range of ΔV_{in} was from 4 ml to 36 ml. A linear relationship (mean $r=0.98$, $p<0.001$) between ΔV_{out} and ΔV_{in} was observed in 19 anesthetized, intubated dogs: $\Delta V_{out} = (f) \Delta V_{in}$, where $f=0.53\pm0.09$ (mean $\pm$ SD). The coefficient, f , ranged from 0.40 to 0.71. These results demonstrate that although f is subject-dependent, ΔV_{out} reliably reflects changes in ΔV_{in} . It is suggested that the technique of inducing a known volume change within the thorax and measuring the volume of air recovered from the trachea could be used as a method for calibrating the pneumocardiogram to obtain stroke volume.

Additional Indexing Words:

Pneumocardiogram Air flow Stroke volume Cardiac output
Noninvasive methods

THE cardiac-induced volume of air moved into the trachea, called the pneumocardiogram (PNCG), bears a relationship to ventricular stroke volume.^{1)–3)} However, a study³⁾ in dogs has demonstrated that the volume of air (ΔV_{pneg}) moved into the trachea during ventricular ejection is consistently less than true stroke volume, and furthermore, the degree of underestimation varies from animal to animal. A typical canine PNCG is illustrated in Fig. 1.

It is generally accepted that the PNCG results from a change in intra-

From the W. A. Hillenbrand Biomedical Engineering Center, Purdue University, West Lafayette, IN, U.S.A.

Address for reprint: Jerry L. Wessale, Ph.D., W. A. Hillenbrand Biomed. Eng. Cntr., Room 204, A. A. Potter Eng. Cntr., Purdue University, West Lafayette, IN 47907, U.S.A.

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Fig. 1. Typical electrocardiogram (ECG), pneumocardiogram (PNCG) and aortic arch pressure recording from a 16-kg dog during normal sinus rhythm. Air flows into the trachea during ventricular ejection and is indicated by a downward deflection in the pneumocardiographic record. The vertical dashed lines define left ventricular ejection time.

thoracic volume.^{1),4)} Therefore, if a known fluid-volume change (ΔV_{in}) is produced within the thorax, and the resultant volume of air (ΔV_{out}) moved in the airway is measured, then the fraction of the thoracic fluid-volume change coupled to the airway, i.e., $f = \Delta V_{out} / \Delta V_{in}$, can be determined. A series of experiments in the dog was carried out to compare a known change in intrathoracic volume, produced by inflating a water-filled bladder within the esophagus, and the concomitant volume of air registered by a pneumotachograph.

METHODS AND PROCEDURES

Materials: To produce a rapid change in intrathoracic volume, water was injected at a fixed rate of flow into an intraesophageal bladder. The apparatus for changing intrathoracic volume consisted of a lax, cylindrical bladder connected to one end of a rigid plastic catheter, the other end of which was connected to a calibrated syringe. The entire syringe-bladder system was completely water-filled.*1

Movement of the syringe plunger was controlled by a specially designed electro-mechanical servo system capable of producing a step in flow velocity. The amplitude of the constant flow was adjustable up to 90 ml/sec for a dura-

*1. The bladder was specially constructed from plastic sheeting (2 ml thick); when fully inflated (≈ 60 ml), it measured 2.5 cm by 13 cm. A residual volume of water (≈ 25 ml) was maintained in the bladder.

tion of approximately 400 msec; thus the maximum volume that could be injected into the bladder was 36 ml. To measure the flow of water into the intraesophageal bladder, i.e. esophageal flow, a specially designed inductive velocity transducer was mechanically coupled to the syringe plunger. For a fixed syringe diameter, velocity of the syringe plunger was calibrated in terms of flow.

Tracheal air flow was measured using a high-fidelity pneumotachograph, which was described in detail previously.^{2),5)} Briefly, the pneumotachograph consisted of a heated Fleisch air resistor (Model #2, Gould, Inc., Recording Systems Div., Cleveland, OH) connected to a high-sensitivity, wide-bandwidth, differential-capacitive pressure transducer. When the pneumotachograph was connected to the endotracheal tube in the anesthetized animal, a record of the output, namely air flow velocity, constituted the PNCG.

Animal preparation: Studies were performed in 19 dogs, ranging in weight from 14.0 to 29.0 kg (21.1 ± 3.8 kg, mean $\pm$ SD). Four animals were anesthetized with sodium pentobarbital (30 mg/kg I.V.). In the remaining animals, anesthesia was induced with sodium thiopental, and subsequently maintained on a mixture of halothane, nitrous oxide and oxygen. Each dog was intubated and placed in dorsal recumbency on a V-shaped animal board. The ECG (lead II) and aortic arch pressure were recorded continuously. Blood pressure was recorded via a #8-French pigtail catheter (Cook, Inc., Bloomington, IN), connected to a strain gauge pressure transducer (Model P23Db, Gould Inc., Oxnard, CA). The pressure-measuring catheter was introduced into a femoral artery and advanced retrograde through the aorta up to the arch. The right cervical vagus nerve was isolated and a bipolar stimulating electrode was placed around the exposed nerve. Vagal stimulation was used to arrest the heart to obtain a quiescent baseline in the PNCG while a known volume of fluid was injected into the intraesophageal bladder.

Procedure: The bladder and catheter were inserted into the esophagus so that the bladder was located in the mid-thoracic region (Fig. 2). Apnea was induced either by a brief period of hyperventilation or by intravenous injection of succinylcholine. During long periods of apnea, positive-pressure ventilation was maintained by a mechanical ventilator (Model 613, Harvard Apparatus Co., Inc., Millis, MA). Following bladder insertion, a series of injections (into the bladder) was performed using different values of ΔV_{in} . The procedure consisted of momentarily arresting the heart via right vagal stimulation, injecting a known volume of water into the intraesophageal bladder, and simultaneously recording the concomitant flow of tracheal air using the pneumotachograph. The duration of an injection typically ranged from 400 to 600 msec.

Fig. 2. Experimental arrangement employing an esophageal bladder and pneumotachograph.

Fig. 3. Typical records of the flow of water into the intraesophageal bladder and of the resultant flow of air out of the trachea.

ΔV_{in} and ΔV_{out} were determined by graphically integrating the esophageal flow and the tracheal air flow, respectively, over the injection period. Data were recorded on a magnetic-tape recorder (Model Store 4D, Lockheed Electronics, Plainfield, NJ) and later displayed on a graphic recorder (Model 2600, Gould, Inc., Cleveland, OH). The graphic records of esophageal and tracheal flows (Fig. 3) were converted to digital form via a graphic-to-digital converter (Graf/Pen^R Model NT-301, Science Accessories Corp., Southport, CT).^{*2} The digitizer was interfaced with a PDP 11/03C laboratory digital computer (Digital Equipment Corp., Maynard, MA). The area under the flow curve was computed using the output from the digitizer; this arrangement, coupled with the use of high-paper-speed recordings, permitted area determinations accurate to $\pm 1.0\%$.

Statistical analysis: The relationship between ΔV_{out} and ΔV_{in} was analyzed using least-squares linear regression. Because ΔV_{out} is zero by definition when ΔV_{in} is zero, regression through the origin was employed.⁶⁾ The null hypothesis was tested at the $p=0.001$ level of significance.

*2. The Graf/Pen^R uses hypersonic impulses generated at the point of a moveable stylus. The operator moves the stylus along the line on a graphic record. Points can be digitized at rates up to 140 points per second, and the device can resolve distances to 0.1 mm.

RESULTS

A typical record of tracheal air flow, superimposed on a record of esophageal flow, is shown in Fig. 3. For a ΔV_{in} of 30.5 ml, ΔV_{out} was 19.7 ml. Therefore, in this example, 64.6% of ΔV_{in} was reflected in ΔV_{out} . Figure 4 illustrates typical results from one dog (#12). The solid line in the figure represents the linear regression line and the dashed line is the line of identity. The results from all 19 dogs are summarized in Table I. The regression coefficients (f) varied from 0.40 to 0.71; the mean ($\pm$ SD) was 0.53 ($\pm$ 0.09). The correlation coefficients (r) ranged from 0.83 to 0.99 (0.977 ± 0.036).

These data show that in all dogs, the volume of air moved in the airway increased with increasing volume of water injected into the intraesophageal bladder. Furthermore, ΔV_{in} and ΔV_{out} were linearly related and significantly correlated ($p < 0.001$). However, f was always less than unity, that is, ΔV_{out} was consistently less than ΔV_{in} .

To compare the ability of the PNCG to track changes in intrathoracic fluid volume in different animals, the data for each animal were multiplied by a scaling factor— $1/f$, the reciprocal of the corresponding regression coefficient, f . The scaled data from all 19 animals are illustrated in Fig. 5. The regression coefficient becomes 1.00; the correlation coefficient for the data from all dogs is 0.99. The solid line in Fig. 5 is the linear regression line, and the dashed lines represent $\pm 10\%$.

Fig. 4. ΔV_{out} versus ΔV_{in} for dog #12. The solid line is the line of regression; the interrupted line represents the line of identity.

Table I. Regression Analysis of ΔV_{out} versus ΔV_{in} *

Dog** I. D.	Weight (kg)	n	f	r	t	Range of Input Volume (ml)
1	17.5	12	0.47	0.99	58.05	8-34
2	26.0	8	0.51	0.98	34.70	8-35
3	14.0	10	0.57	0.99	101.83	7-36
4	19.5	8	0.51	0.99	66.04	7-36
5	25.0	12	0.43	0.99	52.80	5-34
6	29.0	10	0.44	0.99	56.19	10-34
7	21.0	11	0.65	0.99	64.44	10-36
8	19.0	15	0.53	0.99	59.01	9-33
9	23.0	10	0.55	0.98	39.52	14-35
10	21.0	14	0.54	0.99	221.68	6-35
11	17.0	13	0.47	0.99	84.83	11-33
12	22.5	11	0.40	0.97	48.15	13-33
13	22.0	8	0.50	0.98	40.87	10-34
14	15.0	11	0.58	0.99	72.53	7-34
15	22.0	18	0.41	0.97	43.52	8-32
16	19.5	6	0.53	0.83	12.06	5-17
17	26.0	8	0.66	0.99	43.56	6-22
18	20.0	9	0.65	0.97	27.51	6-21
19	22.0	8	0.71	0.99	45.96	4-17

* Heading symbols: n=number of trials; f=regression coefficient (forced through origin); r=correlation coefficient; t=Student's t statistic.

** Anesthesia: sodium pentobarbital (dogs 1-4); halothane (dogs 5-19).

Fig. 5. Scaled output volume versus input volume for 19 dogs. The solid line is the line of regression; the interrupted lines represent $\pm 10\%$.

DISCUSSION

The finding that the volume of air recorded from the trachea is less than the induced volume change within the thorax is consistent with the fact that the stroke volume measured by the PNCG is less than true stroke volume. In a previous study³⁾ in which pneumocardiographic stroke volume (ΔV_{pneg}) was compared with true stroke volume (SV), the regression coefficient, $\Delta V_{\text{pneg}}/\text{SV}$, varied from 0.19 to 0.47 for 5 dogs. The average regression coefficient was 0.35. In the present study, the average regression coefficient for measured tracheal volume versus induced esophageal volume, namely f , was 0.53.

Another similarity between these results and the results of previous work from this laboratory is worth noting. We have reported³⁾ that $\Delta V_{\text{pneg}}/\text{SV}$ is subject dependent. The results of the present study demonstrate that the coefficient f , i.e. $\Delta V_{\text{out}}/\Delta V_{\text{in}}$, is also subject dependent. However, other factors which may affect f , and hence $\Delta V_{\text{pneg}}/\text{SV}$, cannot be ascertained from this study. For example, although f is not flow dependent over the range of esophageal flows (i.e. rates of bladder inflation up to 90 ml/sec) used in this study, it cannot be concluded that f is entirely independent of flow over a wider range.

The fact that the ratio of recovered tracheal volume to esophageal volume is similar to the ratio of pneumocardiographic stroke volume to true stroke volume suggests that the method of injecting a known volume of fluid into an intraesophageal bladder may serve to calibrate the PNCG. For example, a two-point calibration line—tracheal volume recovered for a known volume injected into an intraesophageal bladder—is easily obtained. The volume of air determined from the ventricular ejection portion of the PNCG could then be multiplied by the reciprocal of the slope of the calibration line, yielding the “corrected” pneumocardiographic ventricular stroke volume. Use of this intraesophageal injection calibrating technique will be the subject of a future paper.

REFERENCES

1. Heckman JL, Stewart GH, Tremblay G, Lynch PR: Relationship between stroke volume and pneumocardiogram. *J Appl Physiol* **52**: 1672, 1982
2. Wessale JL, Bourland JD, Babbs CF, Rockenhauser ME, Milewski RC, Geddes LA: Cardiac stroke volume calculation from the pneumocardiogram. *Med Electron* (No 64), p 98, 1980
3. Wessale JL, Bourland JD, Babbs CF, Milewski RC, Rockenhauser ME, Geddes LA: Correlation of the cardiogenic air flow in the respiratory airway (i.e. the pneumocardiogram) with left ventricular stroke volume in dogs. *Jpn Heart J* **26**: 777, 1985
4. Smith NT, Reitan JA: The pneumocardiogram: a potential monitor for the operating room.

- Anesth Analg (Cleve) **49**: 781, 1970
5. Bourland JD: The Pneumocardiogram. A Noninvasive Respiratory Indicator of Cardiac Activity (Ph.D. thesis). Baylor College of Medicine, Houston, TX, 1974
 6. Neter J, Wasserman W: Applied Linear Statistical Models, Richard D Irwin, Inc, Homewood, IL, p 140-175, 1974