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Detection of End-exhalation Period by Airway Thermistor: An Approach to Automated Pulmonary Artery Pressure Measurement

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Monitoring pulmonary vascular pressure (pulmonary artery diastolic and pulmonary capillary wedge pressure) is frequently necessary in critically ill patients. Pulmonary vascular pressures should be measured only during the short time period between the end of exhalation of one breath and the beginning of inhalation of the next breath (the end-exhalation period). The rationale for this practice is that during the end-exhalation period, the magnitude of pulmonary vascular pressures are least dynamically altered either by positive pleural pressure changes caused by a ventilator or by negative pleural pressure changes caused by spontaneous ventilation.

When the respiratory rate is very rapid, the end-exhalation period pulmonary vascular pressure often cannot be determined by examination of the vascular pressure trace alone. In order to more precisely define and identify the pulmonary vascular pressures that exist during the end-exhalation period, the pulmonary vascular and tracheal airway pressure should be recorded simultaneously on paper.[1] However, there are two interrelated major problems with this monitoring recommendation. First, during spontaneous ventilation, decreases in tracheal airway pressure are often extremely small, even though decreases in pulmonary vascular pressure may be large. Second, it is difficult to use tracheal airway pressure to develop a reliable automated system to detect pulmonary vascular pressure during the end-exhalation period. In this report we describe the use of a simple airway thermistor to detect the end-exhalation period and a computer program to automatically and accurately pick the pulmonary vascular pressure during this time period.

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METHODS

The study protocol was approved by the Human Subjects Investigation Committee and informed consent was obtained from all patients. We studied 16 patients who already had indwelling pulmonary artery catheters; 14 patients were intubated tracheally and receiving intermittant mandatory ventilation (IMV), and two patients had tracheas that were not intubated and were breathing spontaneously.

A thermistor equipped flow-directed catheter (Edwards, 93A-302-7F) was modified by cutting off the distal 3 cm, which included the balloon, and which made the thermistor grossly visible. The modified catheter was fixed inside an inspiratory limb T-piece so that the thermistor was directly exposed to inspiratory gas flow (fig. 1). Alternatively, in patients whose tracheas were not intubated, the thermistor was placed inside nasal prongs (fig. 2). The thermistor was connected to a Wheatstone bridge circuit and the bridge balanced so that at the temperature of expired gas there was a zero (baseline) voltage signal. The bridge circuit was connected to a bioelectric amplifier, AC coupled, and the gain adjusted to yield a near full scale signal when a 50- to 200-mV signal was generated by inhalation (relatively cool gas causing a positive pen deflection) and exhalation (relatively warm gas causing a return to baseline).

In patients whose tracheas were intubated, pulmonary vascular and airway pressures (via air-filled pressure line from either the balloon or distal port of the modified flow-directed catheter) were measured with standard transducers and pressure amplifiers. Simultaneous tracings of pulmonary vascular and airway pressures and the airway thermistor signal were recorded on magnetic tape. Airway pressure was not measured in patients whose tracheas were not intubated. The data on the magnetic tape then were printed and analyzed by computer (Digital Equipment Corporation, PDP 11/40) (see appendix) and by two of the author-physicians (JLB, MMM). Computer analysis consisted of sequential examination of 15-s epochs. The end-exhalation period was determined by analysis of the first derivative of the thermistor signal to detect inflection points commensurate with the beginning of inhalation. The end-exhalation period pulmonary vascular pressures which occurred with the highest frequency during the 15-s

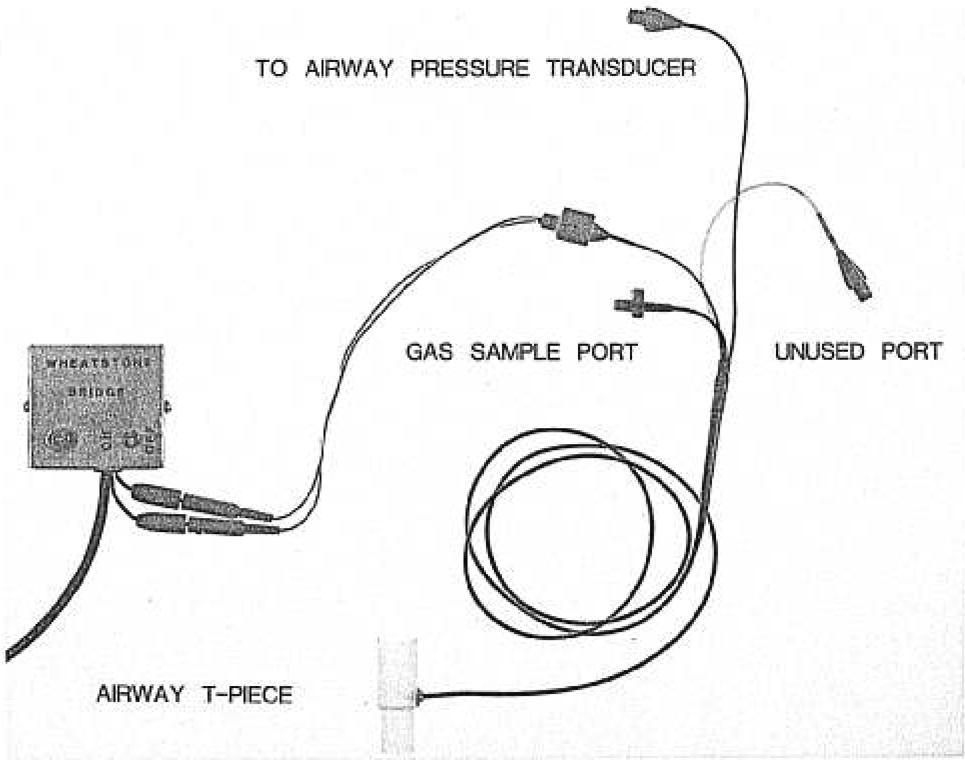

FIG. 1. Photograph of the modified flow-directed catheter used for monitoring respiration in patients whose trachea are intubated. The T-piece is placed in the inspiratory limb of the a respiratory circuit. The photograph shows the proximal (right atrial) port being unused, the distal port connected to a standard pressure transducer to monitor airway pressure, and the balloon port used for sampling inspiratory and end-tidal gas for analysis.

analyzed period were then chosen and displayed. Pulmonary vascular pressures picked by computer were compared with the values picked by the author-physicians from paper tracings of the vascular pressure waveform. The author-physicians had no previous knowledge of the pressure determinations made by each other or the computer.

RESULTS

In all patients we found that the airway thermistor produced a large, clear, interference-free signal. The magnitude of the airway thermistor signals were always large enough to be recognized easily by the authors visually and by the computer, even when simultaneously

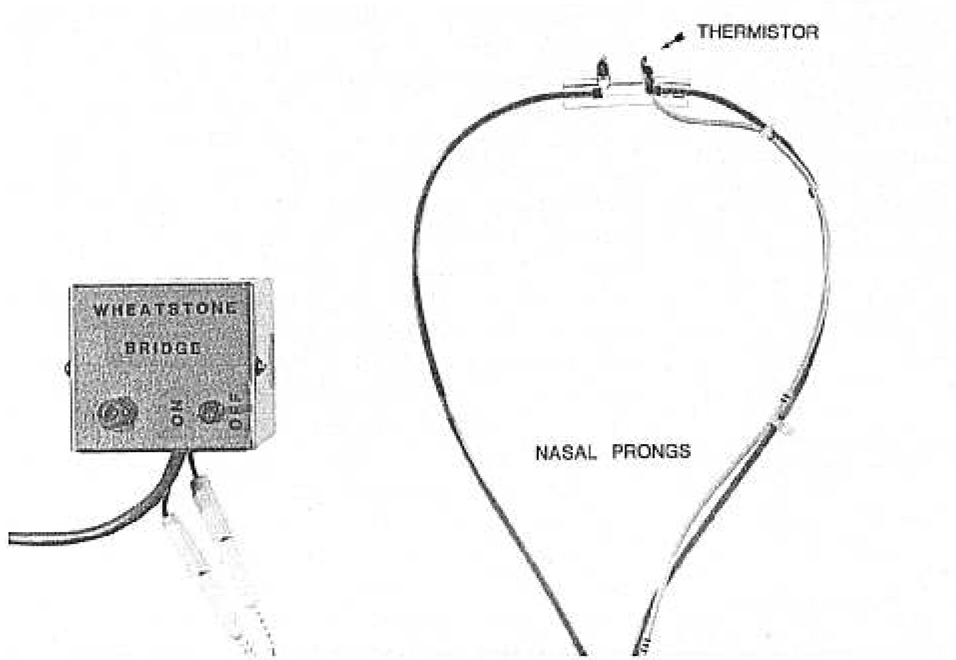

FIG. 2. Photograph illustrating the use of the thermistor with nasal prongs.

recorded airway pressure signals during spontaneous breathing were difficult to detect (fig. 3). In the patient shown in figure 3 (also patient number 3, table 1), the airway pressure trace was of such little utility and the magnitude of the pulmonary vascular pressure traces varied so rapidly, that without the use of the airway thermistor signal, the absolute value of the end-exhalation pulmonary vascular pressure could only be estimated by the physicians to be within a ±3 mmHg range. In addition, a computer program could not be developed that could utilize this poor quality airway pressure signal to automatically record the pulmonary vascular pressure during the end-exhalation period.

Table 1 shows the respiratory pattern (spontaneous/IMV breath/min ratio) and the physician-picked and computer-picked values for systolic and diastolic pulmonary artery pressures for all 16 patients. For all patients the maximum difference between computer- and physician-picked values for the pulmonary vascular pressure during the end-exhalation period was less than 3 mmHg. The largest differences between computer- and physician-picked values for the end-exhalation period pulmonary vascular pressures occurred when the patient's spontaneous respiratory rate was relatively fast (greater than 40/min), and reflects the degree of difficulty of reading the pulmonary vascular pressure trace without precise identification of the end-exhalation period.

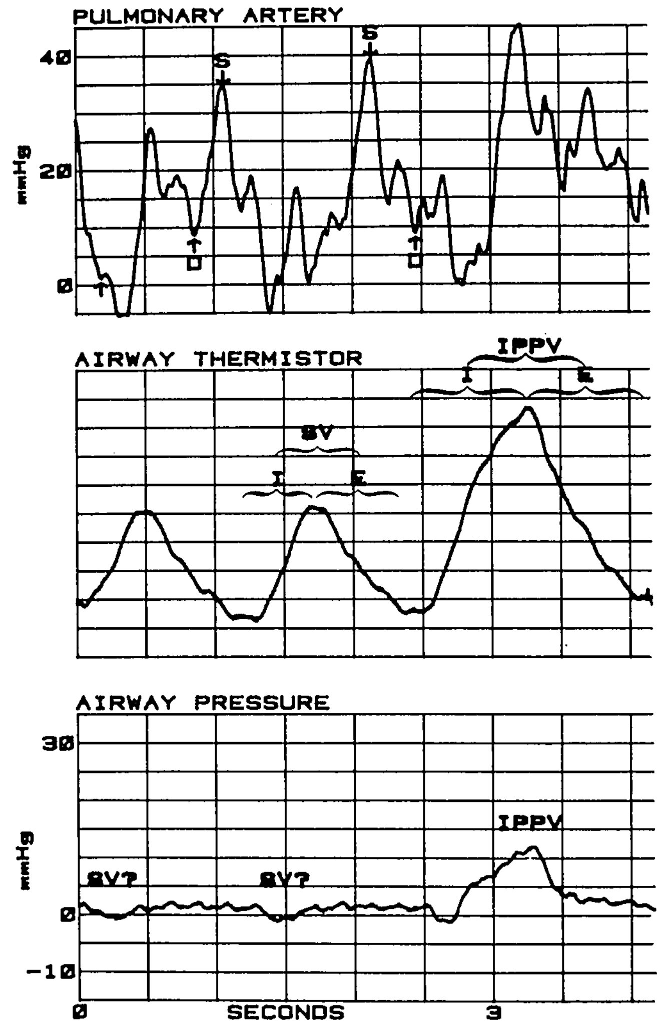

FIG. 3. Simultaneous recordings of phasic pulmonary artery pressure, airway pressure, and thermistor signal from one of our patients on IMV ventilation and breathing at a rate of 54/minute. Note that during spontaneous ventilation the airway pressure becomes only very slightly negative, whereas the pulmonary artery pressure becomes greatly negative. Without the use of the airway thermistor signal, it is only possible to estimate the absolute value of the end-exhalation period pulmonary artery diastolic pressure to be within a ±4 mmHg range. SV = spontaneous ventilation; IPPV = intermittent positive pressure ventilation; I = inhalation; E = exhalation; S = systolic pressure; D = diastolic pressure; ↑ = diastolic pressure excluded by frequency weighting.

Discussion

The end-exhalation period is the only time during the respiratory cycle when the pulmonary vascular pressure trace is unaffected by dynamic changes in pleural pressure. Identification of the end-exhalation period with clinically adequate precision in spontaneously breathing patients may be difficult when using the airway pressure trace alone. Reasons for unsatisfactory airway pressure traces include weak patient effort and low resistance-high compliance breathing circuits. We demonstrated that the end-exhalation period can be determined with great sensitivity and reliability by using the thermistor from a pulmonary artery catheter. The airway thermistor is so sensitive that it records the gas-temperature changes during inhalation with sufficient clarity that a computer program can easily and automatically detect the pulmonary vascular pressure during the end-exhalation period. Even when the spontaneous ventilation rate was rapid, the thermistor signal-based computer program picked values that were always within 3 mmHg of the physicians' estimation. Consequently, our method of automated detection of end-exhalation pulmonary vascular pressures will permit an accurate digital display of pulmonary vascular pressure at end-exhalation; this important specific capability is not commercially available at the present time. Furthermore, the computer algorithm for detection of end-exhalation period pulmonary vascular pressures is adaptable to any system which will accurately detect the end-exhalation period, such as capnographic monitoring or mass spectrometric detection of end-tidal moments.

There are several situations in which the computer may pick erroneous pulmonary vascular pressures. The

TABLE 1. Comparison of Physician- and Computer-picked Pulmonary Artery Systolic and Diastolic Pressures*

Patient Number	Respiratory Rate (Spontaneous/IMV) (Breaths/Min)	PA Systolic Pressure Picked by Physician (mmHg)†	PA Systolic Pressure Picked by Computer (mmHg)	PA Diastolic Pressure Picked by Physician (mmHg)†	PA Diastolic Pressure Picked by Computer (mmHg)
1	0/12	17	17	6	6
2	0/24	40	42	15, 16	16
3	38/16	25, 27	35	10, 11	8
4	0/10	28, 29	32	10	8
5	0/12	25	26	10	11
6	0/18	14	16	9	9
7	2/12	14, 15	15	7	8
8	0/14	20, 21	21	8	8
9*	20/0	20	20	8, 9	9
10*	36/0	33, 36	36	20, 22	21
11	0/10	18	18	11, 12	12
12	0/12	19	19	10	10
13	0/20	30	30	13	13
14	16/16	21	22	5, 6	4
15	0/14	21	21	10	11
16	0/10	38	36	21	22

* Nonintubated Patients; IMV = intermittent mandatory ventilation; PA = pulmonary artery.

† When the physicians picked different values, both values are listed.

computer, like the physician, may fail at picking accurate end-exhalation period pulmonary vascular pressures when the pressure tracing is rapidly distorted by randomly occurring changes in pleural pressure ("bucking," nearly simultaneous spontaneous and ventilator breaths) or by regularly occurring events such as catheter "fling" or "whip" or when significant overshoot is present in the pulmonary artery waveform. Since the computer algorithm sorts the possible end-exhalation period pulmonary vascular pressures during a 15-s monitoring period and chooses the end-exhalation period diastolic pressure that occurred with the highest frequency, erroneous random values are likely to be ignored. Regularly occurring artifacts, such as catheter "whip" or "fling," are likely to be either small and/or equally high and low in both magnitude and frequency of occurrence, and they therefore will be excluded by the frequency-weighted algorithm. Whenever there is any concern that randomly or regularly occurring artifacts may be present, a trained observer (*i.e.*, physician), should always carefully inspect the vascular pressure and thermistor signal waveform configurations.

Our airway thermistor system has a number of other desirable features. First, the airway thermistor device may be readily adapted to monitor respiration and the end-exhalation period pulmonary vascular pressure in spontaneously breathing nonintubated patients. If the device is placed in nasal prongs (fig. 2), and connected in the same way to the bridge circuit and bioelectric amplifier as described previously, a large clear signal will still occur with inhalation, irrespective of whether the mouth is open or closed or oxygen is being administered via the nasal prongs. Second, the airway thermistor also can be used effectively as an apnea monitor in either patients whose trachea are intubated or nonintubated. Third, either the balloon port or the distal port of the modified flow-directed catheter can be used to measure conventional airway pressure in patients whose tracheas are intubated. Fourth, either the balloon port or distal port of the modified flow-directed catheter may be used to sample inspiratory and end-tidal gases for analysis. Fifth, the pulmonary artery catheter may be "recycled" after conventional (vascular) or airway (thermistor) use, in that after appropriate cleaning it can be reused several times as an airway thermistor at virtually no cost. Of course, a lower cost airway thermistor could easily be manufactured.

In summary, we recommend that the airway thermistor signal method supplant conventional airway pressure as a method for detection of respiration, and particularly detection of the end-exhalation period. The airway pressure recording may be an unreliable indication of respiration whenever a spontaneously breathing patient either makes only a weak effort and/or is connected to a ventilation circuit which has either a very low resistance and/or a very high compliance. The airway thermistor provides a clear reliable on-going history of all successful ventilation efforts in all ventilation circuits and, therefore, the airway thermistor signal easily lends itself to accurate computer analysis. Thus, our methodology can be used to generate an accurate digital display of end-exhalation pulmonary vascular pressures and avoid the errors inherent in having inexperienced observers reading the pulmonary vascular pressures from the presently available and relatively nonselective commercial systems.

REFERENCES

1. Berryhill RE, Benumof JL, Rauscher LA: Pulmonary vascular pressure reading at the end of exhalation. ANESTHESIOLOGY 49:365–368, 1978

APPENDIX

Algorithm for Automated Detection of End-exhalation Period Pulmonary Vascular Pressures

1. Store 15 seconds of simultaneously recorded electrocardiogram, pulmonary vascular pressure, and airway thermistor signals, after digitizing, in data buffers. The signals are sampled at 120 Hz.

2. Detect the end-exhalation moment (EEM, the end of the end-exhalation period) from the airway thermistor signal as follows:

a. Pass the digitized airway thermistor signal through a 16-point rectangular digital filter to reduce the electrical noise in the signal.
b. Compute the first derivative (dV/dt) of the airway thermistor signal.
c. Evaluate the computed first derivative (dV/dt) point by point. When dV/dt is greater than 1 volt per second, the first derivative of the airway thermistor signal is evaluated for 0.25 seconds. If the average dV/dt in the 0.25 time period is greater than 1 volt/second, then the initially detected time point (when dV/dt was greater than 1 v/s) is stored as the EEM. If the average dV/dt is less than 1 volt/second for 0.25 seconds, the program returns to evaluating dV/dt point by point. When an EEM has been detected and stored, evaluation of the data buffer (dV/dt) is resumed one second later (120 data points) than the point when the last end-exhalation moment was detected.
d. Proceed as above until the entire 15 seconds of data has been analyzed and all possible EEMs detected.

3. Determine the location in the electrocardiogram data buffer of the R waves of the QRS complexes occurring immediately before each EEM detected above.

4. Define the end-exhalation period of the pulmonary vascular pressure signal as the period between the last two R waves which immediately precede the end-exhalation moment.

5. Detect the pulmonary artery systolic and diastolic pressures within the end-exhalation period as follows:

a. Compute the first derivative of the pulmonary artery pressures (dP/dt).
b. Sort the computed first derivative (dP/dt) of the pulmonary artery pressure signal for inflection points, *i.e.*, where the derivative changes sign. Store all such points.
c. Sort the pulmonary artery pressures that occur at each of the inflection points detected in b above. Store the maximum and minimum pulmonary artery pressures detected as the systolic and diastolic pressures, respectively.
d. Detect and store the pulmonary vascular pressures from each end-exhalation period for the entire 15 seconds of data.

6. Compute the frequency-weighted average pulmonary artery diastolic pressures as follows:

a. Sort all the detected pulmonary artery diastolic pressures into bins which are 2 mmHg wide, *i.e.*, 0–2, 3–4, 5–6, . . . , 29–30 mmHg.
b. Choose the bin with the highest number of entries and compute the average of the pulmonary artery diastolic pressures entered in that bin.
c. Report the pulmonary artery diastolic pressure as the average pressure computed in b above.