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Gas inertia and ventilatory measurements under pressure: methodological considerations

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Hickey DD, Marky DC, Smith RJ. Gas inertia and ventilatory measurements under pressure: methodological considerations. Undersea Biomed Res 1983; 10(4):273–279.—A bag-in-box apparatus with a spirometer was used to measure the ventilatory minute volume in subjects exercising at air pressures up to 6.8 atm. During rest there was good agreement between minute volumes derived from the expired gas in the bag and the sum of tidal volumes from the spirometer, whereas during exercise the bag volume exceeded the spirometer volume by up to 20%. This was found to be due to the inertia of high density gas in the breathing hoses. Given sufficient flow rate the gas would continue to flow from the box to the bag following end expiration and end inspiration. The spirometer would not record this because it only responds to changes in the sum of box and bag volumes, whereas emptying the bag through a gas meter records the volume of gas actually moved. A model was constructed to investigate the phenomenon. It was concluded that many different conventional setups for respiratory measurements may be subject to this type of error. Solutions to the problem include a collapsible tube section downstream from the subject, pneumotachometers, chest-mounted magnetometers, or inductive plethysmographs.

bag-in-a-box
breathing apparatus
diving
forced respiratory maneuvers
gas flow
hyperbaric chamber
inductive plethysmography
inertia
instrumentation
maximum voluntary ventilation
pneumotachometry
respiration
spirometry
ventilation

Expired gas volumes obtained under hyperbaric conditions were found to disagree considerably when measured by two different methods. This discrepancy was observed in measurements performed on air-breathing subjects at pressures up to 6.8 atm. The error was subsequently shown to be due to gas inertia. This phenomenon is considered to be of sufficient general interest to be reported here.

METHODS AND RESULTS

The inertia phenomenon was discovered and studied by using a "bag-in-box" system originally described by Thalmann et al. (1). The system was designed to minimize flow resistance (resistance 1.25 $cmH_2O \cdot liter^{-1} \cdot s$ at a flow of 5 liters/s at a gas density of 8 g/liter). The bag-in-a-box is a 208-liter drum in which is suspended a 200-liter weather balloon (Fig. 1). The inhalation and exhaust hoses coming from an AGA full-face mask (AGA-Spiro, Lidingö, Sweden) have an inside diameter of 6.4 cm and an overall length of 3.7 m. This yields a volume of approximately 12 liters per hose. The check valves are low resistance cone-type flapper valves. Respiratory parameters are measured by a rolling seal spirometer (Model 822, Ohio Medical Products, Madison, WI) that is connected to the inhalation side of the system. To reduce the impedance of the spirometer in high density gas the internal diameter of its hose connection has been increased to 58 mm, providing a 65% larger cross-sectional opening than that of the standard instrument. The mixed expired gas collected in the bag is bled through a gas meter outside the chamber for volume measurement. Thus, total lung ventilation can be obtained both from the gas meter and by summing spirometric tidal volume recordings. Comparisons between such volume measurements obtained simultaneously with the two methods showed up to 20% variation after appropriate corrections. Several possible causes for the volume discrepancies were investigated. The spirometer and the gas meter were recalibrated and found to be correct. Checks for gas leaks at depth were made using helium as a tracer gas: no leaks were found. Operator error was considered and a rigorous investigation into protocol violations was made: none could be established. Finally, a weather balloon was filled through the gas meter at 1 ATA and delivered back to the meter from depth: no volume error was observed.

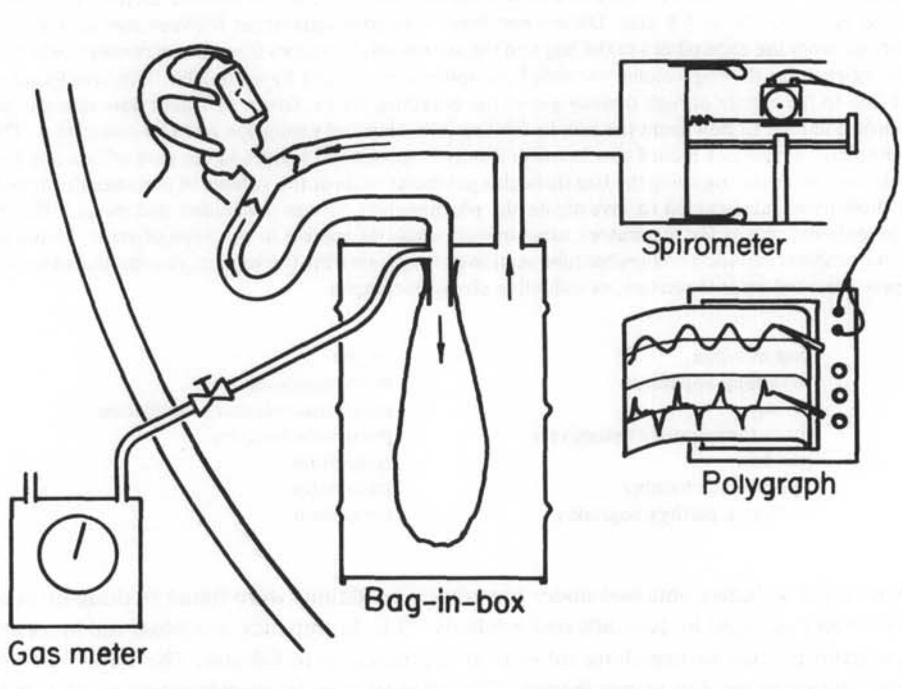

Fig. 1. Schematic of bag-in-box system used for respiratory monitoring in hyperbaric chamber.

Inertia of gas at high density was next entertained as a possible cause. It was reasoned that a high density gas set in motion in the bag-in-box circuit might continue to flow past the check valve block into the bag at the end of inhalation or exhalation. If this happened, the spirometer would not record it, since the spirometer only responds to changes in total system volume. To test this hypothesis a number of experiments were undertaken. First, the check valve block was detached from the face mask and connected to a 2-liter syringe. The bag-in-box system was then compressed to 4.6 atm in the chamber. Using the syringe, 50 strokes were pumped at a rapid rate, aspirating from and expelling air into the system. The resultant volume in the bag was then emptied to the outside of the chamber through the gas meter. In repeated experiments the volume measured at the gas meter, when corrected for temperature and pressure, was 10 to 14 liters greater than the expected 100 liters actually delivered into the system from the syringe. The check valves in the valve block were then replaced with hand-operated valves on both inspiratory and expiratory sides. Fifty rapid strokes were again made using the 2-liter syringe, but this time the inhalation and exhalation valves were operated manually in sequence. The volume collected in the bag was now exactly 100 liters—i.e., there was no overshoot of the bag volume relative to the pumped volume.

To demonstrate the inertia phenomenon more directly a gas circuit excluding the bag-in-box was set up. The inspiration and expiration ports of the check valve block were each connected to a 4-m length of hose. In two different sets of experiments the spirometer was connected either to the inhalation or exhalation hose and the opposite hose was left open to chamber atmosphere. A stroke volume of 2 liters was pumped through the system at different flow rates in separate runs. Instantaneous flow was determined by differentiating the volume signal from the spirometer. With the spirometer on the exhaust side no overshoot was noted at 1 atm at flow rates less than 8 liters/s. At 8 liters/s, however, there was some overshoot, and it reached a maximum of 300 ml at the highest flow rate of approximately 10 liters/s (Fig. 2). Using the same setup at 6.8 atm overshoot was noted at flow rates as low as 2.5 liters/s, and the overshoot increased as the flow rates went up, being maximal at approximately 9.5 liters/s with an overshoot of around 400 ml. The inertia phenomenon could be observed directly, since the transparent (acrylic) valve block allowed the observer to see the cone-shaped inhalation check valve as it opened and allowed gas to go by it after the expiratory stroke of the syringe was completed.

When the spirometer was moved to the inhalation side, similar results were obtained. Thus it can be said that for similar flow rates, the overshoot caused by inertia was the same for either the inspiratory or the expiratory maneuvers and was positively related to absolute pressure.

DISCUSSION

It is important to understand that the gas inertia phenomenon is extremely system specific in that the geometry of the system was critical in setting up the gas flow patterns that were observed. That is to say, the number of bends in the hosing, the length of the hose, the diameter of the hose, the shape and compliance of the valves, and the spirometer itself were all contributing in one way or another to the impact of gas inertia on volume measurements. Nevertheless, it is probable that gas inertia can be the source of an insidious problem of gas volume measurement in any low resistance breathing system at depth, and its impact on a particular experiment can only be determined empirically and will depend on the geometry and the specific setting in which the respiratory monitoring equipment is used, as well as the

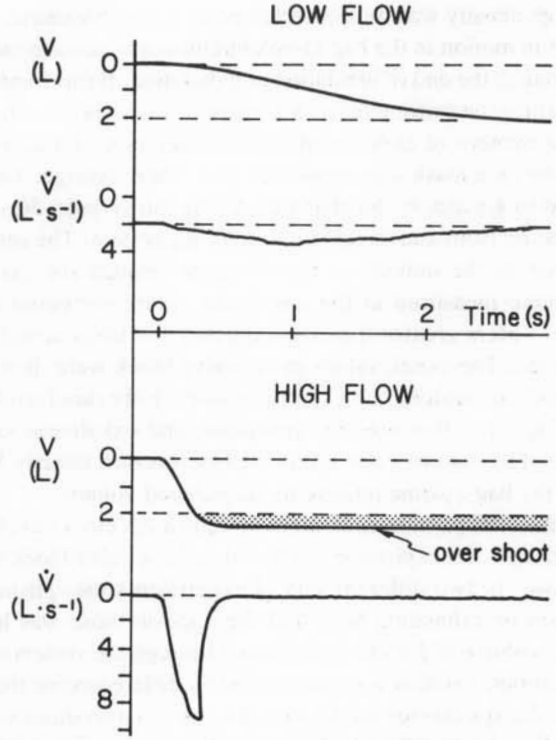

Fig. 2. Typical recordings of gas volume changes and gas flow through hose system at 1.0 atm when 2 liters of air were delivered at low and high flows as described in text. Note volume overshoot induced by high flow.

nature of the particular respiratory maneuver being performed. One particular experimental situation that comes to mind is measurement at depth of maximum voluntary ventilation or forced respiratory maneuvers where high flows are generated, and where frequently the collection apparatus is a simple breathing valve and hose arrangement connected to a gas bag, spirometer, or flow meter. Therefore, it is only prudent that researchers be alert to this potential problem and check their respiratory monitoring system for bias induced by gas inertia.

RECOMMENDATIONS

Several different schemes can be applied that will account for the impact of inertia on gas collection data. In a system using a bag-in-box apparatus that allows the direct measurement of collected gas volume in the bag, a built-in check is automatically provided. If one simply sums the spirometric data and compares that with the actual collected gas volume, one should be able to determine whether or not inertia is affecting volume measurements. [More precise quantitation of the inertia effect requires due consideration of the frequency response of the spirometer at depth (2).] In gas collection setups that do not allow such comparisons other methods must be resorted to. Such a method is placing downstream of the subject a collapsible tube of sufficient cross-sectional area. Thus, at the conclusion of an expiratory effort, at which point the inertia phenomenon manifests itself, flow downstream of the collapsible segment will generate a subambient pressure inside the segment such that the segment will collapse and interrupt flow (Fig. 3). The effect of a collapsible segment on overshoot was demonstrated in separate experiments (Fig. 4). Such a device appears to be adequate to interrupt inertia-generated flow during expiration. In a system with sufficiently large inspiratory hose volume, however, the collapsible segment will not interrupt the inertia phenomenon generated during inspiration, since pressures at the mouthpiece and collapsible segment will be slightly greater than downstream pressures. Therefore the segment will not collapse. Other means around the inertia phenomenon include respiratory measuring devices such as pneumotachometers, chest-mounted magnetometers, or inductive plethysmographs.

The problem of gas inertia at depth may not be limited to creating bias in volume measurements. It is interesting to speculate that gas inertia in a diving environment may impose subtle physiological consequences on the diver that would depend on the geometry of his breathing equipment, the density of the breathing gas, and the pattern of breathing. The experimental

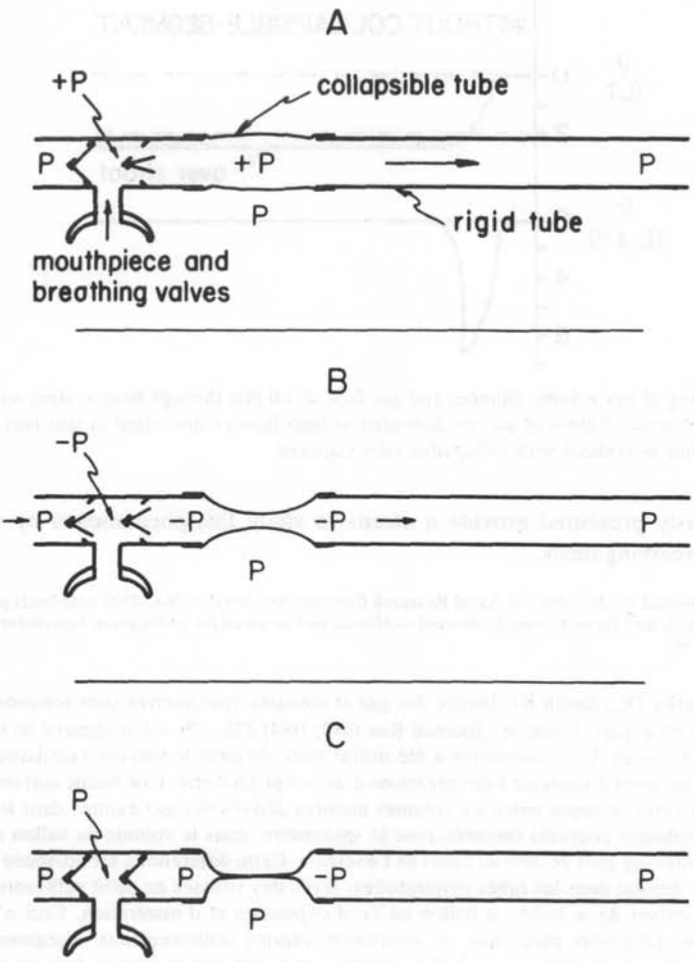

Fig. 3. Schematic of a proposed solution to bias induced by gas inertia in expired volume recordings: a collapsible tube is inserted downstream of the breathing valves. P represents ambient pressure, + P is pressure greater than ambient, and − P is pressure lower than ambient. *Panel A:* pressure and gas flow situation during expiration. *Panel B:* situation at end of expiration, gas column in rigid tube retaining inertial flow. *Panel C:* situation immediately following *B* with collapsible tube interrupting flow.

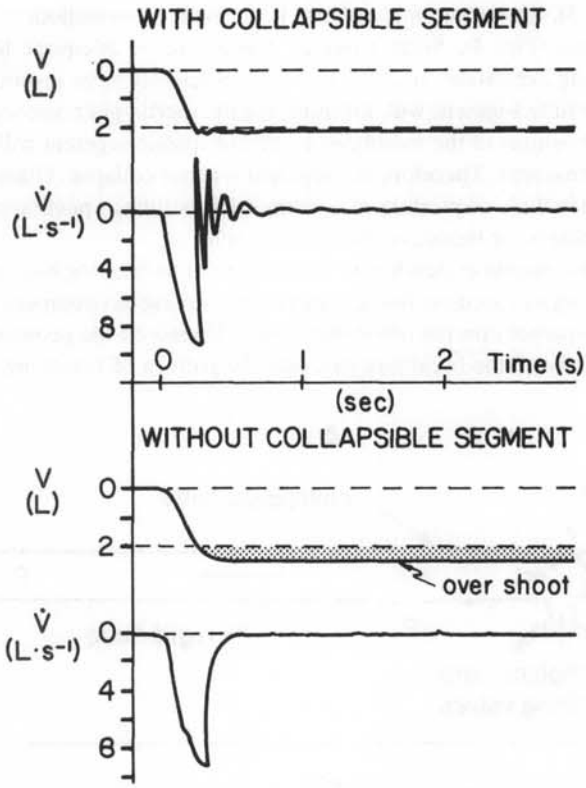

Fig. 4. Recording of gas volume changes and gas flow at 1.0 atm through hose system with or without collapsible segment while 2 liters of air are delivered at high flow as described in text (see also Fig. 3). Note minimal volume overshoot with collapsible tube segment.

methods previously presented provide a means to study this phenomenon by varying gas density in long breathing tubes.

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Hickey DD, Marky DC, Smith RJ. Inertie des gaz et mesures ventilatoires sous pression: considérations méthodologiques. Undersea Biomed Res 1983; 10(4):273–279.—Un appareil de type "ballon-en-boîte" et équipé d'un spiromètre a été utilisé pour mesurer le volume ventilatoire minute chez des sujets en cours d'exercice à des pressions d'air jusqu'à 6.8 atm. Une bonne correspondance a été obtenue à l'état de repos entre les volumes minutes dérivés des gaz expirés dans le ballon et la somme des volumes courants mesurés avec le spiromètre, mais le volume du ballon surpassait celui du spiromètre par plus de 20% au cours de l'exercice. Cette différence a été attribuée à l'inertie des gaz à haute densité dans les tubes respiratoires. Avec des vitesses de débit suffisantes, les gaz continuaient à passer de la boîte au ballon en fin d'expiration et d'inspiration. Ceci n'a pas été observé avec le spiromètre parce que cet instrument répond seulement aux changements de la somme des volumes de la boîte et du ballon, tandis que le vidange du ballon dans un gazomètre donne le volume des gaz actuellement déplacés. Un modèle a été construit pour investiguer ce phénomène. Il a été conclu que plusieurs montages conventionels différents pour les mesures respiratoires peuvent être sujet à ce genre d'erreur. Les solutions à ce problème incluent l'utilisation d'une section de tube flexible en aval du sujet, de pneumotachomètres, de magnétomètres fixés au thorax, ou de pléthysmographes inductifs.

ballon-en-boîte
appareil respiratoire
plongée sousmarine
manoeuvres respiratoires forcées
débit gazeux
chambre hyperbare
pléthysmographie inductive
inertie
instrumentation
ventilation volontaire maximale
pneumotachométrie
respiration
spirométrie
ventilation

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