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Water Vapor Calibration Errors in Some Capnometers: Respiratory Conventions Misunderstood by Manufacturers?

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Incorrect calibration has been included in several recently introduced CO_2 analyzers. They display a value of "P_{CO_2}" internally calculated as $F_{CO_2} \times P_b$ rather than $F_{CO_2}(P_b - 47)$ where P_b is barometric pressure. This conceptual error appears to have been introduced because new sampling catheter material has become available that effectively removes water vapor before samples reach the sample cell. This seems to have led some manufacturers to assume, incorrectly, that the 47 mmHg factor used to compute P_{CO_2} in patients would no longer be needed. Users can test whether this error is present in an instrument by testing the effect of wet *versus* dry gases, and make appropriate corrections if the errors are present. Manufacturers should promptly correct this error in all instruments sold previously. (Key words: Measurement technique, capnography: calibration errors; water vapor. Monitoring: capnography.)

SEVERAL NEW INFRA-RED carbon dioxide analyzers (capnometers or capnographs) have been marketed utilizing an incorrect internal calculation of P_{CO_2} from the known calibration cylinder $\%CO_2$. They display a value of "P_{CO_2}" internally calculated as $\%CO_2/100 \times P_b$ rather than $\%CO_2/100 \times (P_b - 47)$. The problem arises over the handling of water vapor during conversion from instrumental $\%CO_2$ to patient P_{CO_2}.

Terminology

The standard symbols used in respiratory physiology were set forth in 1950 by Pappenheimer.[1] The conversion from fractional concentration in dry gas to partial pressure saturated at body temperature was used as self-evident after Paul Bert demonstrated the prime role of partial pressure,[2] was explicitly stated by Rahn and Fenn,[3] and formally defined by Otis.[4]

1. STPD: Standard Temperature (0° C) and Pressure (760 mmHg), Dry.
2. BTPS: Body Temperature and Pressure, Saturated (assumed 37°, 47 mmHg).
3. P_b = Barometric pressure, mmHg.
4. F_{CO_2}: Fractional concentration of CO_2 in dry gas (STPD), where $F_{CO_2} = \%CO_2/100$.
5. P_{CO_2} (or P_{O_2}): Partial pressure of CO_2 (or O_2), in mmHg, of gas saturated with water vapor in the body at body temperature (BTPS), assumed (unless otherwise specified) to be 37° C, computed as:

$$P_{CO_2} = F_{CO_2} \times (P_b - 47) \qquad (1)$$

The Problem

Capnometers are comparators. They have normally been considered as dry gas analyzers.[5] They are calibrated using a cylinder with a known F_{CO_2}. They measure an unknown gas from a patient, containing water vapor which may dilute the sample. As a first step, some method is needed to correct for this dilution by water vapor, to determine the true F_{CO_2} of the patient sample, *i.e.*, the "dry gas" CO_2 concentration in the sample. The next step is to convert F_{CO_2} to P_{CO_2} (wet) because physicians want to know P_{CO_2} as it affects gas exchange in a patient, whether inspired (after becoming saturated in the trachea) or alveolar (end-tidal) gas.

Confusion has arisen because new sampling catheter materials have become available that are permeable to water and hence can largely remove water vapor from expired breath. If these new catheter materials work perfectly, gas entering the capnometer sample cell will have the water vapor concentration of room air, whether sampled from a cylinder of dry gas or from an airway saturated with water vapor at 37° C. The analyzed concentration, F_{CO_2}, is that of dry gas because it is standardized with dry gas of a known concentration of CO_2. However, the incorrect assumption has then been made by some manufacturers that the instrument, since it always reads gas of the same (room air) humidity, can be calibrated to read P_{CO_2} by:

$$P_{CO_2} = F_{CO_2} \times P_b \qquad (2)$$

This yields the "P_{CO_2}" in the analyzer cell, but not in the patient, where water vapor is always present at 47 mmHg at 37° C. If one uses equation 2, 5% CO_2 is set to read 38.0 mmHg, at sea level with P_b = 760, whereas the correct setting is (0.05 × 713) = 35.65 mmHg. The former setting causes alveolar P_{CO_2} to read 6.6% too high.

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An example of the widespread occurrence of this error occurs in a recent paper specifically dealing with accuracy of P_{CO_2} measurement in which From and Scamman[6] incorrectly computed P_{CO_2} of a 6.94% CO_2 calibrating gas to be 51.4 mmHg at 737 mmHg barometric pressure. The correct P_{CO_2} is 47.9 mmHg, an error of 3.5 mmHg. Four of the six capnometers they tested read even higher than their erroneously high "correct" value. From their data, the actual P_{CO_2} errors (*vs.* 47.9 mmHg) compute to be +10.1, +5.1, +6.1, and +10.1 mmHg, respectively, for Datascope Accucap®, Hewlett-Packard 47210A, Narkomed 3 Capnomed®, and Novametrix Capnogard® 1250.

Compensation by Users for In-built Calibration Error

The error can be corrected by entering into the memory of the capnometer a falsely low value for the calibration cylinder %CO_2. If water vapor has no effect on the reading, enter actual %CO_2 × $(P_b - 47)/P_b$.

Correction for Actual Water Vapor Errors

If the sampling catheter does not fully equilibrate the sample water vapor to that of room air, correction is not straight forward. Water vapor may have three effects on the reading: First, it dilutes the CO_2. Second, it may increase the reading of CO_2 by a phenomenon called "pressure broadening," in which CO_2 molecules that have absorbed an infrared photon can transfer that extra kinetic energy to H_2O and then be ready to accept another photon. Water is more able than O_2 and N_2 to accept this energy. And, third, water molecules may absorb some of the bands of infrared light used to measure CO_2.

It thus becomes necessary to perform an empiric calibration in which the reading of samples saturated with water vapor are tested against the same gas when dry. This can be done in several ways.

First, 5% CO_2 from a cylinder can be used to set the meter. This gas may then be bubbled through water at 37° C and sampled to measure the difference of reading, if any, waiting for at least 2 min to insure that the sampling catheter becomes as wet as it will in use. This requires a carefully constructed humidifier.

Second, the capnometer may be compared to a mass spectrometer sampling the end-tidal gas from a subject after calibrating both with the same dry gas. Mass spectrometers used in medicine do not sense water vapor, but detect all other gases and force their total to sum to 100%, thus providing a dry gas analysis, whether the sample was wet or dry. This method assumes that the mass spectrometer conversion to P_{CO_2} is correct, or relies on its %CO_2 result, which cannot be directly compared to automated capnographs which only display P_{CO_2}.

Third, the most useful method is to record the "dry-out" change of the capnometer output when the sample line is suddenly switched from long-term sampling of a subject to the dry calibration gas.[7] Initially, the calibration gas will become humidified by the walls of the sampling catheter and cuvette, and may thus read somewhat low. After some seconds or minutes, the cuvette will dry out and the reading will drift upward by a few percent and stabilize at the dry level. The magnitude of this change depends on all the factors described above, the dilution by water, the pressure broadening, and the absorption by water of infrared light of the same wavelengths used to analyze CO_2 in the particular analyzer, and will be greater when the capnometer is used with a catheter not permeable to water vapor or water, such as teflon, polyethylene, vinyl, or nylon (in short lengths).

If such a wet-to-dry transition can be demonstrated and measured, then calibration procedure must be to increase the dry gas calibration by a factor equal to the observed dry/wet ratio. For example, gas from a cylinder containing 5.00% carbon dioxide reads 35.6 mmHg after sampling long enough for the catheter and cell to become dry. Expired gas from a patient is then sampled for several minutes, allowing the sample system to become wet. When the sample line is suddenly switched from the airway to the cylinder of 5% CO_2, the reading is 34.6 for 15 s, then rises to 35.6. The dry-to-wet ratio is then 35.6/34.6 = 1.029. To correctly calibrate the instrument, with a P_b = 760, the dry gas reading should be set to:

$$P_{CO_2} = 0.05 \times (760 - 47) \times 1.029 = 36.7 \text{ mmHg} \quad (3)$$

To accomplish this with most modern capnometers, the user will have to enter a false value for the calibration cylinder, calculated as:

$$\text{False } CO_2 = \text{Actual } \% \ CO_2 \times [(P_b - 47)/P_b] \times (\text{dry/wet}) \text{ ratio}, \quad (4)$$

which, in this example, would be 4.83% CO_2.

Does your capnograph have this problem? It may not be obvious, since, in many computer-based units, one is instructed to sample the known gas and push a "cal" key, and let the internal computer set the P_{CO_2} reading. If you know the gas CO_2 concentration, after performing the calibration, sample that gas again and read the result. If 5% reads 38 mmHg, an error is present. In order to calibrate such instruments correctly, you will have to insert a false CO_2 concentration into the instrument's memory. If there is no wet/dry difference, insert F_{CO_2} × (713/760).

Several commercial capnometers incorrectly compute patient P_{CO_2} from measured %CO_2 concentration, neglecting to account for water vapor in the lung. This error, being hidden in the computerized calibration procedure, cannot be corrected by users. Users can test whether this error is present in an instrument by re-reading the calibration gas after calibration is completed, and noting whether cylinder P_{CO_2} reads $F_{CO_2}(P_b - 47)$ or $F_{CO_2}(P_b)$. It may be helpful to also test the effect of wet *versus* dry gases. Users can compensate for the error by entering an altered $\%CO_2$ value for the calibration cylinder. Manufacturers should promptly correct this error in all instruments previously sold.

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