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# Frequency Response of Long Mass-spectrometer Sampling Catheters

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**It was hypothesized that the long lengths of sampling catheters required when a mass spectrometer is multiplexed to more than one operating room limit the upper frequency at which a gas concentration may be determined accurately. This possibility has not been investigated. Known step changes of $CO_2$ were generated by a solenoid valve driven by an electronic timer that was adjustable from 0.1 to 10 Hz. The valve alternated between 100% $O_2$ and 7% $CO_2$ in 50% $O_2$ and balance $N_2$. $CO_2$ concentration was monitored by a mass spectrometer after the gas passed through a 3.7 m Teflon® catheter or through 30 m Teflon®, nylon, polyethylene (PE), or polyvinylchloride (PVC) catheters. Gas flow for all catheters was adjusted to 1.1 ml/s. The peak-to-peak output of the mass spectrometer was read from a storage oscilloscope. The 3.7 m catheter caused a 10% error at 5.5 Hz (330/min). In sharp contrast, 30 m catheters made from Teflon®, PVC, and PE caused errors greater than 10% at only 0.6 Hz (36/min). The 30 m nylon catheter passed 1.1 Hz (66/min) with a 10% error. Teflon®, PVC, and PE are not suitable materials from which to make long catheters sampling $CO_2$. Because the frequency response of the nylon catheter appeared similar to that of a low-pass filter, an electronic circuit was designed and tuned to extend the high-frequency response of the catheter. With the circuit in place, the frequency at which a 10% error occurred in the measurement of $CO_2$ improved from 1.1 Hz (66/min) to 2.2 Hz (132/min). This simple circuit, which may be retrofitted to existing units, is an effective method to extend the frequency response and accuracy of long catheters sampling $CO_2$.** **(Key words: Gas analysis: anesthetic. Mass spectrometry: respiratory.)**

MONITORING OF ANESTHESIA gases from more than one anesthetizing location using a centrally located mass spectrometer is becoming widespread.[1] Often long sampling catheters are required to access remote locations. Rapid changes in sampled gas concentration are predictably "smeared" by convection and diffusion of gas molecules at the concentration change interface during transit down the catheter. The degree of "smearing" is proportional to the length of the catheter and is independent of the flow through it.[2] Smearing limits the maximum frequency (highest respiratory rate) at which highest and lowest gas concentration values can be determined accurately. It is of clinical relevance to determine this limit at which long sampling catheters are accurate. Additionally, we were unable to find literature regarding the question of whether or not the material from which the catheter is made effects the high-frequency response. Finally, because, in practice, long sampling catheters are often unavoidable, we developed and tested a simple electronic method to restore a portion of the lost high-frequency response.

## Materials and Methods

This investigation consists of two experiments. In experiment one, a Perkin-Elmer mass spectrometer (MGA 1100) was set up to sample directly from each of five catheters. The reference catheter was the standard sampling catheter supplied by Perkin-Elmer, was made from Teflon®, was 3.7 m long (0.43 mm ID), and had a flow rate of 1.1 ml/s. The remaining four catheters were each 30 m long: 0.86 mm ID polyethylene (PE), 0.86 mm ID nylon, 0.79 mm ID Teflon®, and 1.0 mm ID polyvinylchloride (PVC). The flow rates of these long catheters were adjusted to 1.1 ml/s to match the flow rate of the reference catheter by adding short (<1 m) lengths of 0.28 mm ID Teflon® catheter in series at the mass-spectrometer end. The rapid change in gas concentration was generated by a solenoid valve (Humphrey 062E1), driven from 0.1 to 10 Hz, switching between 100% $O_2$ and a gas containing 7% $CO_2$ in 50% $O_2$ and balance $N_2$. The mass-spectrometer output was routed to a storage oscilloscope (Tektronix 564B) from which data were taken. The error is reported as the percentage difference between the peak-to-peak values and the true value as determined from the 3.7 m catheter.

For experiment two, the mass spectrometer sampled only from the nylon catheter. Nylon was chosen over other long-catheter materials because it had demonstrated the best high-frequency performance. Data were taken as before, either with the output of the mass spectrometer fed directly to the oscilloscope or through the electronic compensation circuit described in the following.

The compensator (fig. 1) is simple in theory and construction. The smearing occurs in a nearly symmetric pattern, both on the leading and trailing edges of the waveform,[2] reducing the amplitude of its high-frequency information. This information must be restored in order to improve the high-frequency response of the system. The first differential of a waveform contains only its high-frequency information. However, the result is not symmetric. Differentiating the waveform twice, thus obtaining the second differential, restores symmetry and retains the

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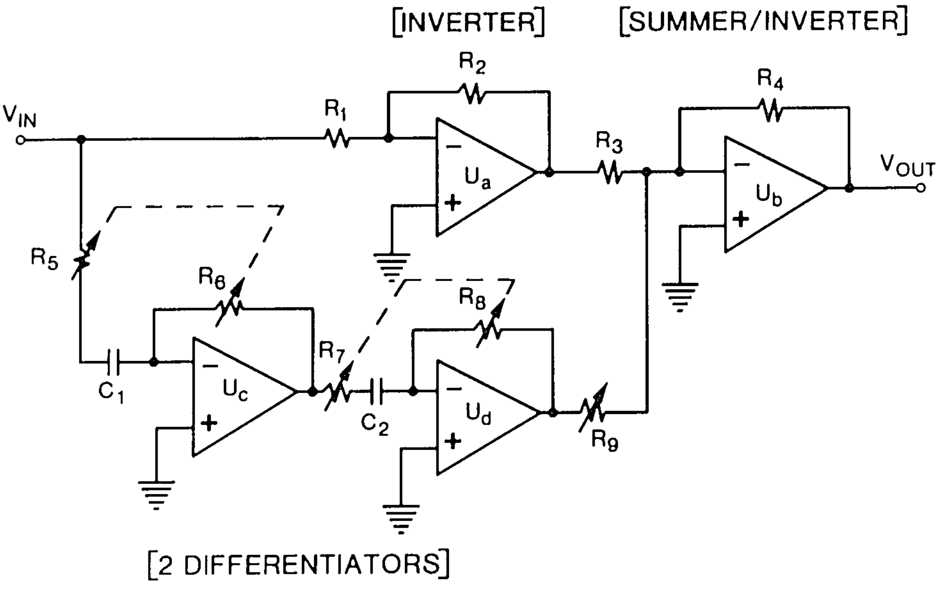

FIG. 1. Schematic diagram for compensation circuit. $R_1$ – $R_4$ = 100 K ohm; $R_5$ – $R_9$ = 100 K ohm; $C_1$,$C_2$ = 0.22 microfarad; $U_a$ – $U_d$ = operational amplifiers, Radio Shack TL094CN Quad Bifet.

high-frequency information. The compensator amplifies this high-frequency information and adds it to the original signal.

The compensator was tuned in the following manner. An amplitude *versus* log frequency plot was constructed for the nylon catheter (fig. 2, *closed circles*) and the half-power frequency determined. (Half-power occurs when the amplitude has decreased to 0.707 of the original.[3]) The period of this frequency was multiplied by 0.016 (determined empirically; see "Discussion") to calculate the time constants of the differentiators. With the input frequency set to the half-power frequency, the amount of compensation was adjusted to restore the amplitude to 100%.

## Results

For experiment one, the frequency response of the five catheters is shown in figure 3. The 3.7 m long Teflon®

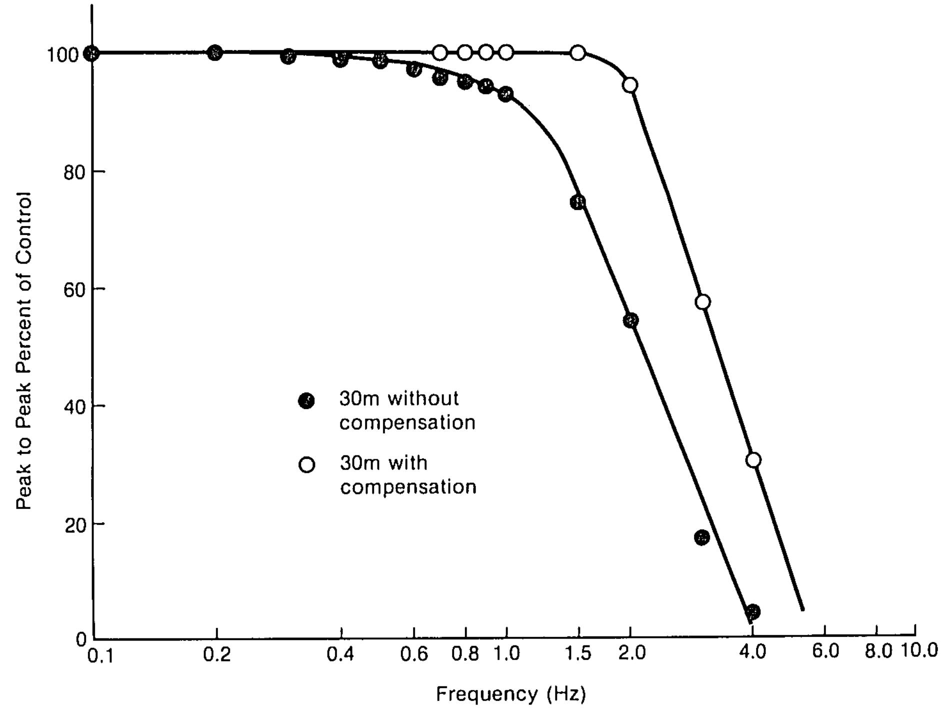

FIG. 2. Compensated and uncompensated frequency responses for the 30 m long 0.86 mm ID nylon catheter.

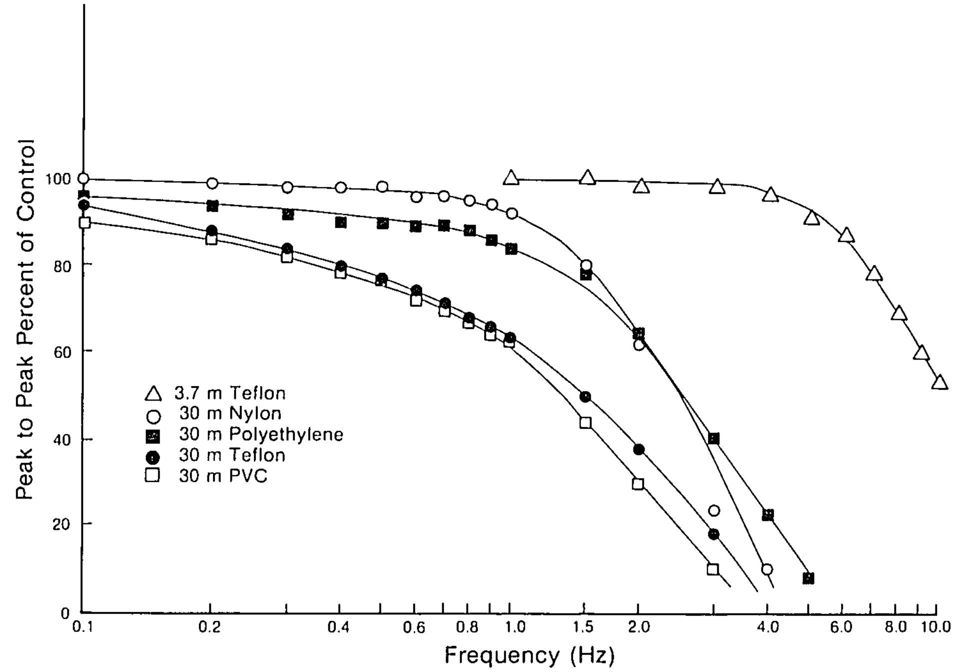

FIG. 3. Frequency response of 3.7 m Teflon® (0.43 mm ID), 30 m nylon (0.86 mm ID), 30 m polyethylene (0.86 mm ID), 30 m Teflon® (0.79 mm ID), and 30 m polyvinylchloride (PVC) (1.0 mm ID) sampling catheters to 5% $CO_2$ at a flow rate of 1.1 ml/s.

reference catheter exhibited excellent frequency response from less than 0.1 Hz to only a 10% error at 5.5 Hz (330/min). The PVC and 30 m Teflon® catheters showed an appreciable error already at 0.1 Hz (6/min), which increased rapidly with increasing frequency. The nylon and PE catheters showed less error with the nylon catheter, having a 10% error at 1.1 Hz (66/min). If one accepts no more than 10% as being an acceptable level of error, then, for the 30 m lengths, the PVC catheter failed at 6/min, the Teflon® at 9/min, the PE at 34/min, and the nylon at 66/min.

For experiment two, the compensated and uncompensated frequency responses for the 30 m long nylon catheter are shown in figure 1. The uncompensated response shows an error of 10% starting at a frequency of 1.1 Hz (66/min). With the compensator active, the frequency at which a 10% error occurs has been extended to 2.2 Hz (132/min).

## Discussion

An accurate high-frequency response is mandatory in mass-spectrometer systems used for monitoring gas concentrations. It is possible for the respiratory rate of a child under halothane anesthesia to exceed 1 Hz (60/min) and, therefore, generate gas-concentration changes of twice that frequency. If the catheter will not pass the information accurately, then the input signal to the computer that detects the highest and lowest values will be in error and the data reported will be in error. Furthermore, the error will be in a direction such that one might be prompted to *decrease* the ventilation of the patient.

If accurate information is to be obtained from a mass-spectrometer system that depends on long sampling catheters, then the materials making up these catheters must be carefully chosen. Using $CO_2$, we have shown that nylon has the least error when compared with PE, PVC, or Teflon®. It is unlikely that the large errors present with these latter three materials were due just to the transport mechanics of a concentration change down the catheter. Because of their large magnitude, we believe that the mechanism underlying these errors must have involved adsorption of $CO_2$ into the catheter material itself. This adsorption of $CO_2$ into PVC and Teflon® was such that even at 0.1 Hz there was an appreciable error. This error also may have been due to a high permeability of $CO_2$ in these materials. Clearly, Teflon® and PVC are not suitable for long sampling catheters for multiplexed mass spectrometry. Polyethylene, although somewhat better, nonetheless, had a marked limitation in high-frequency response. Adsorption of $CO_2$ into nylon is not significant, as indicated by no error at 0.1 Hz. The excellent high-frequency response displayed by the 3.7 m Teflon® catheter indicates that the native mass-spectrometer frequency response far exceeded that permitted by the 30 m catheters. The even-shorter segments of Teflon® catheter used to regulate the flow in the long catheters then would have a negligible effect in determining their frequency response.

We used $CO_2$ because it is most useful in manual or computer detection of inspiration and expiration in order to detect end-tidal values of itself and other, simultaneously measured gases. In addition, $CO_2$ has the largest percentage change in value from inspiration to expiration, thus putting the most stringent high-frequency requirement on a sampling system. Other gases, such as the potent inhalational vapors, will likely have different transport characteristics down long sampling catheters, but were not studied in these experiments.

There are at least two approaches to compensate for the smearing and distortion introduced by long sampling catheters. Because the breathing frequency data of the waveform are intact, a computer could correct the parent signal using a high-frequency digital filter whose gain increases with frequency. Not only would this require a powerful and expensive computer, but the time necessary to program it would be out of proportion to the benefit realized, particularly for the many channels necessary for complete anesthetic gas analysis. Therefore, it was elected to perform the necessary compensation with an analog circuit.

The dashed curve in figure 4 shows the theoretic response for a low-pass filter with a half-power frequency of 1 Hz. This curve appeared much like the uncompensated curve (fig. 1, *closed circles*). To extend maximally the frequency response and yet remain within 5% of the true value, the compensator should be adjusted to yield a curve similar to the solid curve in figure 4.

In tuning the compensator, if the time constants of the differentiators were set shorter than 0.016 of the period of the half-power frequency, then the output became noisy. If they were set longer, then overcompensation greater than 5% occurred just below the half-power frequency.

Because the compensator is matched to a specific gas and a specific catheter length, just one compensator is required for each gas analyzed if all of the catheters are identical in length. Because it is unlikely that the distances to various sampling locations will all be equal, the catheters should be cut to the length required for the most distant location and the excess from the closer rooms coiled conveniently.

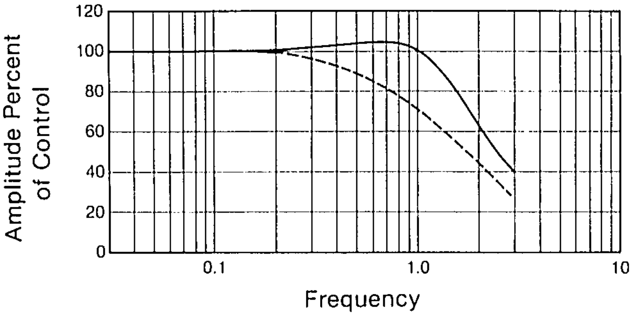

FIG. 4. *Dashed line* represents the theoretic frequency-response curve for a catheter with a half-power frequency of 1 Hz. *Solid line* represents the theoretic response curve for maximum possible compensation with no more than 5% error. Redrawn from Alley CL, Atwood KW: Electronic Engineering. New York, John Wiley and Sons, 1962, p. 303.

The cost of the compensator was less than $15 (not including power supply).

We conclude that of the long catheters tested, the nylon catheter permitted by far the best high-frequency response for a $CO_2$ waveform. Only this catheter performed acceptably at clinically relevant frequencies. Catheters made from Teflon®, PE, or PVC may cause a clinically relevant decrement in the accuracy of multiplexed mass spectrometry. We further conclude that restoration of accuracy to clinically acceptable limits is possible through a simple and inexpensive electronic compensator.

## References

1. Ozanne GM, Young WG, Massei WJ, Severinghaus JW: Multipatient anesthetic mass spectrometry. ANESTHESIOLOGY 55: 62–70, 1981
2. Goodwin B: Factors influencing the accuracy of mass spectrometry measurements, The Medical And Biological Application Of Mass Spectrometry. Edited by Payne JP, Bushman JA, Hill DW. London, Academic Press, 1979, pp 50–55
3. Alley CL, Atwood KW: Electronic Engineering. New York, John Wiley and Sons, 1962, pp 301–307