We used capnometry during high-frequency oscillatory ventilation (HFOV), and compared CO₂ measurements at the distal and proximal ends of an endotracheal tube with arterial CO₂ values. Ten white rabbits (mean weight, 2.00±0.2 [SD] kg) underwent tracheostomy under anesthesia with pentobarbital. The trachea was intubated with an endotracheal tube with a second lumen for sampling respiratory gas at the distal tip. Capnometry was performed through the lumen (CO₂d) and the proximal end of the endotracheal tube (CO₂p). The internal carotid artery was cannulated to sample blood for measuring arterial blood gases. The differences between CO₂d, CO₂p, and PaCO₂ were measured. Only the relation between CO₂d and PaCO₂ was good (r = 0.915). We concluded that capnometry can be used during HFOV to estimate PaCO₂ provided that respiratory gas is sampled from the distal tip of the endotracheal tube.

Methods

The experiment was performed on ten white rabbits weighing 1.16 to 2.21 kg (mean, 2.0±0.2 [SD] kg). The rabbits were anesthetized with intravenous pentobarbital, with supplemental doses as needed to suppress the corneal reflex. After tracheostomy, the animals were intubated with a 4-mm internal diameter tracheal tube with a second lumen for sampling respiratory gas (Mallinckrodt, Glens Falls, NY). The distal tip of the tube was positioned just above the carina under x-ray guidance. The internal carotid artery was cannulated for sampling blood to analyze PaCO₂. The analysis was performed with anABL2 blood gas analyzer (Radiometer, Copenhagen).

The rabbit lungs were ventilated by using the HFOV mode of a Hummingbird BMO 20N mechanical ventilator (Mera, Tokyo). The operating conditions were set as follows: stroke volume, 4, 6, 8, 10, and 12 ml; frequency, 15 cycles/s; inspiration-expiration ratio, 1:1; mean airway pressure, 3 cm H₂O; fresh gas flow rate, 1 or 2 L/min. At each setting, the PaCO₂ and the CO₂ concentration of the respiratory gas (r-CO₂) were measured simultaneously. The respiratory gas was sampled through the second lumen of the tracheal tube from just above the carina (r-CO₂d) and from the proximal end of the endotracheal tube.
of the tube (r-CO$_{2d}$). The r-CO$_{2}$ was measured with a Nellcor (Hayward, Calif) N-1000 monitor (Fig 1). The sampling rate was 50 ml/min; length of sampling line, 1.52 m; response time, 85 ms.

During HFOV, r-CO$_{2}$ is constant, and the monitor, expecting the cyclic appearance and disappearance of CO$_{2}$ in the respiratory gas, does not report numeric data but rather sounds an alarm if apnea is detected. To measure r-CO$_{2}$ during HFOV, a three-way stopcock was placed between the respiratory circuit and the sampling tube of the monitor. The cock was turned to sample the respiratory gas and the room air alternately (Fig 2). These artificial fluctuations in the CO$_{2}$ concentration created the cyclic appearance and disappearance of CO$_{2}$; thus, the monitor reported minimum and maximum CO$_{2}$ concentrations with each respiratory cycle. We turned the cock to create artificial fluctuations of CO$_{2}$ concentration at least ten times, and established the stability of the numeric values displayed by the monitor for end-tidal CO$_{2}$.

RESULTS

In all rabbits, low stroke volume induced hypercarbia. The lower the stroke volume, the higher the r-CO$_{2d}$ and PaCO$_{2}$. Because severe bradycardia or bigeminy pulse occurred at stroke volume settings under 4 or 6 ml, the experiment was discontinued at that stroke volume. The total number of sample points was, therefore, 88 for PaCO$_{2}$ and r-CO$_{2d}$ (PaCO$_{2}$ = 1.33 $[r$-CO$_{2d}$] - 10.1 [r = 0.915, p<0.001]) (Fig 3). In two rabbits, r-CO$_{2p}$ was not monitored; therefore, the number of total sample points for r-CO$_{2p}$ was 72. The r-CO$_{2p}$ values at stroke volumes of 4 and 6 ml were as low as those at other settings, and the agreement between r-CO$_{2}$ and PaCO$_{2}$ was very poor (r = 0.206, p>0.5).

DISCUSSION

Capnometry is a very useful monitoring procedure in critically ill children. Capnometry provides measurements of the CO$_{2}$ concentration in the patient's respiratory gas. In addition to guiding ventilatory management, capnography assists the clinician by rapidly detecting critical events such as breathing circuit disconnection and kinking of the endotracheal tube. However, in small infants, if the respiratory gas is sampled at the slip joint of the endotracheal tube, the capnograms are distorted, and the expired CO$_{2}$ concentration may not accurately reflect PaCO$_{2}$.

In small infants, the respiratory gas must be sampled from the distal tip of the endotracheal tube just above the carina to obtain close agreement between r-CO$_{2}$ and PaCO$_{2}$.

In the present study, respiratory gas was sampled from the distal tip of the tube. Therefore, it was possible to detect the capnometric waveforms accurately in our small rabbits when using HFOV.

The response time is an important factor in monitoring end-tidal CO$_{2}$ in small infants. Nellcor engineers creatively reduced the volume of the CO$_{2}$ analyzing chamber such that the N-1000 monitor is able to use a sampling flow rate of 50 ml/min and still achieve an instrument response time similar to that of other capnometers that use a higher sampling flow rate. Its response time is shorter than 0.1 s. This makes it possible to detect the capnographic waveforms accurately even in small infants.

High-frequency oscillatory ventilation is used especially for small preterm infants. With this mode,
there are no inspiratory and expiratory phases such as occur during conventional mechanical ventilation. Therefore, there is no such thing as "end-tidal CO₂" during HFOV. Some capnographs, including those obtained with the Nellcor monitor, cannot measure the concentration or partial pressure of CO₂ unless cyclic fluctuations are present, as there are during conventional mechanical ventilation. In the present study, we placed a three-way stopcock between the respiratory circuit and the sampling tube of the monitor, and turned it at least ten times to sample the respiratory gas and room air alternately at an interval of 1 s. This technique made it possible to produce square waveforms of CO₂ concentration; the machine also displayed the partial pressure of the CO₂.

If the machine will work when waveforms are linear, we can monitor the partial pressure of CO₂ even during HFOV without manipulation of the stopcock. At the proximal opening of the endotracheal tube, the respiratory gas is mixed with fresh gas. Its mixing rate is considerably affected by setting conditions such as fresh gas flow rate and stroke volume. Therefore, the CO₂ concentration at this point usually does not approximate PaCO₂.

In the present study, r-CO₂p showed no significant relation with PaCO₂, because eliminated gas is diluted by fresh gas significantly at the airway opening. However, r-CO₂d showed good correlation with PaCO₂, probably because the dilution of eliminated gas by fresh gas is not significant at the level of the distal tip of endotracheal tube. It is therefore concluded that capnometry using distal sampling of respiratory gas accurately reveals the relationship between PaCO₂ and r-CO₂d even in small subjects during HFOV.

REFERENCES