High-frequency Animal Ventilator Using a Loudspeaker and Its Gas Exchange Characteristics

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Abstract A high-frequency ventilator was designed using a loudspeaker as a piston, driven by a power-amplifier. A sine-wave signal was introduced into the amplifier from an electronic oscillator. The mechanical and gas exchange characteristics of the ventilator were studied in vitro and in dogs.

The volume output per stroke, when open to air, was between 100 and 200 ml up to 7 Hz, then gradually decreased as the frequency increased. A Wright respirometer appeared to measure the volume flow fairly accurately up to 14 Hz. The pressure output against a closed volume of 1.1 liters achieved a maximum of 29 mmHg at 7 Hz. It gradually decreased as the frequency was changed from 7 Hz. The loudspeaker worked in such a way that the volume output decreased considerably when it was forced to move against a closed space to generate pressure.

Adequate ventilation was achieved in all dogs from 1.4 to 10 Hz. At 14 Hz, the results were variable, and at 20 Hz and above, gross hypoventilation always resulted. The $PaO_2$ values were always over 440 mmHg when 0.8 liter/(kg·min) of oxygen was supplied into the respiratory circuit.

A speaker ventilator has the advantage of easy assembly and the possibility of applying various flows by electrical control. Its disadvantages are a lack of power and the difficulty in establishing ventilatory volumes without actual measurement.

An animal ventilator is usually constructed, like a Harvard-type ventilator, by combining a motor, a piston, and a cylinder with some sort of valve mechanism. Recently, artificial ventilation at a frequency considerably higher than the ordinary respiratory rate (high-frequency positive pressure ventilation: HFPPV) was reported a useful means of achieving artificial ventilation under certain conditions (HEIJMAN et al., 1972; SJÖSTRAND, 1977; KLAIN and SMITH, 1977; BOHN et al., 1980; BUTLER et al., 1980). It is not easy, if not totally impossible, to modify a conventional ventilator for this purpose. As an alternative, we designed an HFPPV...
animal ventilator, using a loudspeaker (SUWA, 1980). We report here the gas exchange characteristics of the HFPPV and the power of the revised ventilator (V₂ System). The preliminary study performed by a prototype ventilator using a commercially available loudspeaker (V₁ System) has already been published elsewhere (SUWA and TAGAMI, 1981). A part of the data for the V₁ System is included in this paper for reference.

STRUCTURE OF THE INSTRUMENTS

The fundamental structure of the instrument is shown in Fig. 1. The main part of the ventilator is a cone-type dynamic loudspeaker. This loudspeaker was fixed to a small baffleboard and a small wooden cabinet (internal volume of 1.1 liters) and an attempt was made to attach, air-tight, a respiratory circuit to this board using bolts. At one end of the respiratory circuit, a gas inlet port was prepared. We could not prevent leakage of the cabinet completely, and this served as a gas outlet (Fig. 1). This loudspeaker was driven by an ordinary stereo-amplifier (Pioneer SX-717, single channel continuous output being 48 W), to which a sine-wave electric signal was introduced at various frequencies between 1 and 30 Hz (NF Circuit Design Block Co., Inc. E-1011).

In choosing the loudspeaker for the V₁ System, we had tested various commercial models, but only one model proved satisfactory (Fostex, FW 200). For the V₂ System, we obtained a specially-made powerful speaker from the same company (a modified type of FW 200). The mechanical and electrical characteristics of

![Diagram of the speaker-ventilator](image)

Fig. 1. Upper, block diagram of the speaker-ventilator; lower, detailed schema of the main body of the speaker-ventilator. The gas outlet is required in principle, but actually the leakage through the cabinet wall served as the gas outlet.
Table 1. Characteristics of the two speaker units.

<table>
<thead>
<tr>
<th></th>
<th>V₁ System</th>
<th>V₂ System</th>
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<tbody>
<tr>
<td>Nominal diameter (cm)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Electrical impedance (Ω)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Resonance frequency (f₀; Hz)</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>Acoustic output level (dB/W at 1 m)</td>
<td>91</td>
<td>88</td>
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<tr>
<td>Effective radius (cm)</td>
<td>8.1</td>
<td>8.1</td>
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<tr>
<td>Magnet weight (g)</td>
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<td>1,660</td>
</tr>
<tr>
<td>Total magnet flux (Mx)</td>
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<td>160,000</td>
</tr>
<tr>
<td>Flux density (G)</td>
<td>8,000</td>
<td>10,500</td>
</tr>
<tr>
<td>Electrical input (W)</td>
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<td></td>
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<tr>
<td>continuous</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>peak</td>
<td>100</td>
<td>160</td>
</tr>
<tr>
<td>Maximum displacement at 2 Hz (mm)*</td>
<td>9.2</td>
<td>10.8</td>
</tr>
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* This was calculated from the volume output measured by a Wright respirometer and from the effective radius, assuming that the cone is completely rigid.

the two speaker units are shown in Table 1. We made no measurements as to the rigidity of the cone material, but for the unit of the V₂ System we attached a flat aluminum plate (diameter of 16.2 cm, 2 mm thick) over the cone in order to make the cone heavier and more rigid.

EXPERIMENTAL METHOD

In vitro experiments. At various frequencies, the maximum flow output of the V₂ System at its peak capacity was measured in three ways: first, using a screen pneumotachograph (Nihon Kohden TP601T) and second, using a Wright respirometer. Since the accuracy of the measuring instruments was questionable at such high frequencies and at such high flow rates, and the results were conflicting, a third method was also used. The loudspeaker was attached to a relatively large cabinet (13 liters). The cabinet was first filled with oxygen. While the oxygen concentration inside the box was being measured continuously with a mass-spectrometer (Shimadzu MASPEC R-2A), the system was turned on and the respiratory circuit opened. The oxygen in the cabinet was exchanged with the room air and the oxygen concentration inside the cabinet fell rapidly. This fall in oxygen yielded a good single exponential curve and was quite reproducible. The flow output was calculated by the time-constant of this curve and the cabinet volume.

The loudspeaker worked in such a way that its volume output decreased when the speaker-cabinet (1.1 liters) was totally closed. In other words, the displacement of the cone and the voice coil was far less when it was forced to move against a closed space and to generate pressure than when it was allowed to move freely in the open air. In order to analyze the cone displacement against a closed airspace, the pressure in the closed cabinet was measured at various frequencies at the maximum capacity of the two systems. Volume displacement of the cone...
(d\(V\)), which is equal to the tidal volume (\(V_T\)), under this condition was calculated by the formula,

\[
dV = -\frac{V}{\gamma} \frac{dP}{P},
\]

where \(\gamma\) is the adiabatic constant for air and oxygen (1.4), \(V\) is the cabinet volume, \(P\) is the atmospheric pressure and \(dP\) is the peak-to-peak pressure deviation produced (see APPENDIX).

The maximum capacity of the \(V_1\) System was determined by some unusual noise that the loudspeaker generated. The maximum capacity of the \(V_2\) System was limited by the ability of the amplifier rather than the loudspeaker itself (see DISCUSSION).

*Animal experiments.* Ten dogs, weighing 7.5 to 17.4 kg, were anesthetized with ketamine (30 mg/kg) given intramuscularly, then intubated and placed on the speaker-ventilator (\(V_2\)) starting at 3 Hz. A femoral artery was cannulated for arterial pressure measurement and for arterial blood sampling to analyze the blood gases (Radiometer ABL-2). Endotracheal \(P_{CO_2}\) was measured either by a mass-spectrometer or by an infra-red analyzer (AIKA RAS-41).

In the study using the \(V_1\) System, we have already established that dogs weighing 10 kg can be ventilated adequately at 3 and 5 Hz with an oxygen flow of 0.8 liter/(kg·min). Knowing that the \(V_2\) System is considerably more powerful than the \(V_1\) System, we examined mainly two points. First we studied the gas exchange characteristics at a frequency of 1, 1.4, 2, 3, 5, 7, 10, 14, and 20 Hz, and attempted to define a frequency band in which this ventilator could be used satisfactorily. Second, the effects of the changes in oxygen flow rates were studied at a flow rate of 0.2, 0.4, 0.8 liter/(kg·min) and occasionally even higher than these at 3 Hz in comparison to the 0.8 liter/(kg·min) setting in the previous study. In addition, the positional effect of the oxygen inflow port was also examined. The first point was set at the end of the respiratory circuit, next to the connection to the endotracheal tube as shown in Fig. 1. The second point was set at the tip of the endotracheal tube. In this case, oxygen was given via a catheter connected to the tracheal end of the endotracheal tube.

**RESULTS**

*In vitro experiments*

The flow outputs of the \(V_2\) System at various frequencies measured by three different methods are given in Fig. 2. The first and second methods yielded considerably different results, the difference depending greatly upon the frequencies used. The third method using an \(O_2\) washout technique resulted in values close to those found by the Wright respirometer, though they tended to be slightly higher. The discrepancy between the Wright respirometer and \(O_2\) washout method be-
Fig. 2. The maximum ventilatory volume output of the $V_2$ system when the respiratory circuit is open to air measured by three different methods. The abscissa is the frequency in Hz (log-scale). The ordinate is the minute volume of the ventilator ($V_{Es}$). It may be seen that the oxygen washout method and the Wright respirometer yielded similar results, while the results with a pneumotachograph are totally different.

came larger as the frequency exceeded 14 Hz.

The pressure outputs of the $V_1$ and $V_2$ Systems against a closed airspace are shown in Fig. 3. The two systems show a very different frequency-pressure profile. At lower frequencies the pressure output of the two systems did not differ very much, while at higher frequencies, the $V_2$ System was considerably more powerful. In Fig. 3, the pressure output of another system using a very large speaker (FW 400; 38 cm diameter) is also shown. The pressure outputs were considerably less throughout the frequency range tested (see Discussion).

The volume outputs of the $V_2$ System calculated from the pressure readings, using Eq. 1, were indicated as broken line in Fig. 3 and found far less than those in Fig. 2, except in the range of 28 to 40 Hz. The lung can be viewed as a kind of leakage when it is viewed from the ventilator; a leakage with a resistance of airway and a capacitance of lung-thorax system. We may, therefore, assume the maximum ventilatory volume in the animal used to be somewhere between

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Fig. 3. The pressures generated by the loudspeaker against a closed air space (1.1 liters for $V_1$ and $V_2$, 2.14 liters for 38 cm loudspeaker) were plotted against frequencies. The estimated minute ventilation of the $V_2$ System is also shown (-----). The tidal volumes in ml of the $V_1$ and $V_2$ Systems can be read from the pressure scale since it is numerically almost the same as the scale in pressure in $V_1$ and $V_2$ ($1100/(1.4 \times 760) \approx 1.03$). For the 38-cm loudspeaker, doubling the pressure (mmHg) yields the tidal volume (ml) ($2140/(1.4 \times 760) \approx 1.97$).

The animal experiments

The $V_2$ System succeeded in achieving adequate ventilation from 1.4 to 10 Hz (Fig. 4). Even at 14 Hz, half of the dogs were ventilated enough to achieve $P_{a_{CO_2}}$ under 50 mmHg. At 20 Hz and above, $P_{a_{CO_2}}$ rapidly increased and arrhythmia appeared. For reference, the values obtained by using the $V_1$ System are also shown.

The relationship between the oxygen flow rate and $P_{a_{CO_2}}$ values at 3 Hz is shown in Fig. 5. The mean $P_{a_{CO_2}}$ value at 0.8 liter/(kg·min) (27.1 mmHg) in this system was almost exactly equal to that of the $V_1$ System (27.8 mmHg), suggesting that the two systems have a similar gas exchange ability at 3 Hz.

There was a slight decrease in $P_{a_{CO_2}}$ when the gas inlet port was transferred from the end of the respiratory circuit of the ventilator (Fig. 1) to the tip of the endotracheal tube. For example, at 0.2 liter/(kg·min) flow, they were 33.9 and
Fig. 4. $P_{\text{a}CO_2}$ values obtained by the V$_2$ System (mean ± S.D.) are shown. Numericals in parentheses represent the number of measurements. Those for 3 Hz include all values using various oxygen flow rates and two different inflow points. For other frequencies, the flow rates are usually 0.4 or 0.8 liter/(kg·min) and the inflow point is that shown in Fig. 1.

Fig. 5. The relationship between oxygen flow rates and $P_{\text{a}CO_2}$ measured at 3 Hz. Numericals in parentheses represent the number of measurements.

$P_{\text{a}CO_2}$ values were always more than 440 mmHg when a flow rate of 0.8
liter/(kg·min) was used. They became lower at lower flow rates, though sufficiently high (at least 120 mmHg) to achieve adequate oxygenation of the blood. This probably was not indicative of the disturbed pulmonary gas exchange, but again it was mostly due to the leakage of the ventilator. In other words, the ventilator sucked the room air into the cabinet during the expiratory phase. The negative pressure during the expiratory phase might possibly have created some airway closure. We measured the oxygen concentration of the airway only in a few instances. We could not analyze the quantitative relationship of the two factors, the leakage and the airway closure.

DISCUSSION

The loudspeaker used in the V1 System was an ordinary commercial “woofer” (a loudspeaker for low-frequency reproduction). The dogs up to 13 kg were ventilated successfully at frequencies from 2 to 7 Hz by this system (SUWA and TAGAMI, 1981). With the intention of widening this range, we tried to use more powerful loudspeakers. Two models, Yamaha 3871 and Fostex FW 400, with a diameter of 38 cm and maximum outputs of 97 and 95 dB/W, and an electric input allowance of 200 and 150 W, were first examined. Surprisingly, however, both hardly succeeded in ventilating a dog at any frequency tested. As seen by the pressure output data (Fig. 3), large speakers do not generate much pressure, although their flow output may be enormous in open air. The big loudspeakers with big cone sizes are not suitable for such pressure ventilation.

The loudspeaker used in the V2 System was made specially for the present purpose by the Fostex Co.; its characteristics are given in Table 1. With this system, the applicable range of frequency was widened considerably. Paco2 values at 10 Hz were sufficiently low to ensure that this ventilator can deliver adequate ventilation up to this frequency. At the lower end of the frequency band, we probably did not use the power of this loudspeaker to its maximum capacity. The power-amplifier used was of an old model, incorporating a condensor-coupling circuitry; the power-output was decreasing at 12 dB/oct below 8 Hz. It was likely that the amplifier did not supply with a sufficient power to the speaker.

A loudspeaker ventilator has one serious disadvantage; we have no easy way of estimating tidal volume. It appears that a pneumotachograph is not satisfactory. The Wright respirometer was acceptable, but it loaded a dead space and resistance to the animal, thereby producing a rise in Paco2. Therefore, we could only keep it attached to the circuit for a short period in dog experiments.

The leakage of the loudspeaker box, which we could not totally control, must have affected the experiment in several ways. This probably caused a power loss and created a discrepancy between the ventilatory volume of the ventilator and that delivered to the animals. It could have caused a decreased oxygen concentration, because the ventilator sucks the air in through the point of leakage.

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We are obviously considering applying this ventilator to patients. In addition to improving the above-mentioned drawbacks, we further need to check several points: safety, sturdiness, and easy handling. Disinfection is another factor to be considered. At this moment, we hesitate to use it for clinical purposes.

The $V_1$ and $V_2$ Systems, however, may have several usages. The $V_1$ System can be assembled easily at a very modest cost, and it may serve as a good starting point for studying HFPPV. According to the company, the loudspeaker for $V_2$ System may soon be available commercially.

The physiology and the clinical application of HFPPV remain to be studied. A technique of measuring the ventilatory volume with minimum dead space and resistance is required. The mean intra-tracheal pressure must be adjustable. While a sine-wave was used as an electrical signal for the present study, a different flow pattern may be more efficient for gas exchange. Although we have made no actual study so far, this loudspeaker-ventilator may have one advantage over the motor-piston-cylinder type HF-ventilator: Various wave-forms can be applied simply by modifying the input oscillator signal.

We thank the Fostex Company for kindly supplying us with a specially-made loudspeaker, and Dr. Shun-ichi Tabuchi and Mr. Yoji Honda of the Fostex Company for their cooperation during the course of the study.

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APPENDIX

When a loudspeaker oscillates against a closed air space ($V$), it generates positive and negative pressure. In the frequencies we tested, the changes in volume and pressure occur adiabatically (HADDAD and RICHARDS, 1968), that is,

$$PV^\gamma = K$$

where $\gamma$ is the adiabatic constant (1.4 for oxygen and air), or the ratio of the specific heat at constant pressure and constant volume. Differentiating it by $P$ and rearranging it yields the formula given in the text (Eq. 1). Since the $dP$ and $dV$ are small enough in comparison to $P$ and $V$, $dV$ may be calculated directly by using pressure change as $dP$.

REFERENCES


