THE USE OF ULTRASONIC ENERGY TO VAPORIZER ANAESTHETIC LIQUIDS

P. CABLER, L. A. GEDDES AND J. ROSBOROUGH

SUMMARY

Ultrasonic energy, provided by a commercially available water vaporizer, was used to vaporize methoxyflurane, halothane, and chloroform. The vaporizer was placed directly in the respiratory line, and the anaesthetic liquid was vaporized one drop at a time. Anaesthesia was maintained for periods up to 6 hr in horses, ponies, calves, sheep, dogs, and one pig. This method of vaporizing liquids is applicable to a wide variety of anaesthetics. It is easily controlled, and the same vaporizer can be used with a wide range of sizes of subjects. The vaporizer can be placed directly in the respiratory circuit, and adds almost no resistance to breathing.

The use of ultrasound in anaesthetic procedures has been confined largely to the humidification of inspired gases (Herzog, Norlander and Engstrom, 1964; Cheney and Butler, 1970; Malik and Jenkins, 1972), and to the administration of topical anaesthetic agents (Christoforidis, Tomasheski and Mitchell, 1971; Martin, Isreal and Stovin, 1972) to inhibit tracheobronchial reflexes. To date, the authors have been unable to locate studies in which ultrasonic energy has been used to vaporize volatile anaesthetic agents used for general anaesthesia. This paper reports on the adaptation of an ultrasonic nebulizer to vaporize halothane, methoxyflurane and chloroform to maintain anaesthesia in 28 animals ranging in weight from 12 to 545 kg.

METHODS AND MATERIALS

A sketch of the ultrasonic vaporizing equipment is shown in figure 1. The vaporizer consists of a Model 650 hand-held nebulizer (Monaghan Co., Littleton, Colorado) in which the ultrasonic energy developed by a piezoelectric crystal, vibrating at 1.5 mega-Hz, is coupled via a column of water to a hemispherical copper-foil cup. The anaesthetic liquid is delivered one drop at a time, from a glass syringe reservoir via a needle mounted above the foil cup. Between the syringe reservoir and the needle is a silastic tube which is pinched closed by a spring-loaded solenoid. A pulse of current delivered to the solenoid momentarily opens the silastic tube and allows one drop of the anaesthetic liquid to fall into the foil cup. At the same time, the ultrasonic oscillator is turned on for a preset time which is longer in duration than is required to vaporize the drop of anaesthetic liquid. The electronic drop control unit controls drop rate and size and turns on the ultrasonic oscillator for a time which is slightly longer than is needed to evaporate the drop of anaesthetic liquid.

The vaporized drop of anaesthetic is carried into the respiratory system by placing the vaporizing chamber directly in the airway. The "gas out" port is connected to the inspiratory tube; the "gas in" port is connected to the tube leading from the gas-mixing manifold and carbon dioxide absorber, as shown in figure 2.

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In order to permit the use of positive pressure in the airway, the upper end of the glass syringe reservoir is capped and connected, via a small-bore tube, to the vaporizing chamber to equalize the pressure in the reservoir (fig. 1). In this way the drops of anaesthetic agent can be delivered equally well with ambient or positive pressure in the airway, thereby allowing use of the system in association with intermittent positive pressure ventilation.

The amount of anaesthetic agent delivered is varied by controlling two parameters of the delivery system: drop size and rate. The drop size is controlled by the duration of the pulse of current delivered to the spring-loaded solenoid. In practice, the drop size is fixed and the amount of anaesthetic delivered is controlled by varying the drop rate. Figure 1 shows the drop control unit which also turns on the ultrasonic oscillator. An oscillator "on-time" control has been provided to select the duration of vaporization. Ordinarily this control is preset according to the vapour pressure of the agent; therefore, control of the amount of anaesthetic delivered is achieved by setting the "drop rate" control. The amount of anaesthetic delivered during the procedure can be determined at any time by viewing the glass syringe reservoir. A totalizing drop counter, connected across the spring-loaded solenoid, provides additional information on the amount delivered, expressed in terms of the total number of drops. When graph recording is used, the drops of anaesthetic delivered can be registered by recording the voltage pulses delivered to the spring-loaded solenoid.

The method of using the ultrasonic vaporizer in this study is shown in figure 2. The ultrasonic vaporizer is in series with the respiratory circuit which contains a carbon dioxide absorber, a mixing manifold, a rebreathing bag and a pressure gauge. Connected to the manifold are storage tanks of oxygen and nitrous oxide, each with a pressure regulator and flowmeter. With this system, it is possible to secure independent control of the amount of oxygen, nitrous oxide and the liquid anaesthetic; the latter is controlled by adjustment of the drop rate. The oxygen and nitrous oxide flow rates were adjusted to keep the bag from collapsing.

Dogs, calves, pigs, sheep, ponies and horses were maintained under gaseous anaesthesia for periods ranging from 1 to 6 hr. All dogs were anaesthetized without premedication. Anaesthesia was induced in three dogs with a mixture of droperidol and fentanyl (Innovar-Vet) and pentobarbitone (7.4 mg/kg). In the remaining dogs, anaesthesia was induced with thiopentone, administered i.v. (20 mg/kg). The calves, sheep, pigs, ponies and horses received premedication with rompun (Xylozine, Bay Va 1470) i.m. in a dose of 0.2 mg/kg for the ruminants and 2.0 mg/kg for the ponies, horses and pigs. Induction of anaesthesia for those species other than canine and porcine was achieved by administration of an aqueous solution containing 50 mg/ml of dextrose and 50 mg/ml of guaiacol glyceryl ether and 2 mg/ml of thiopentone. The dose of guaiacol glyceryl ether was 110 mg/kg and that of thiopentone was 4 mg/kg. In the pigs, anaesthesia was induced with nitrous oxide in oxygen to which was added the volatile anaesthetic. In each animal, after the induction of anaesthesia, the trachea was intubated with a cuffed endotracheal tube which was connected to the anaesthetic circuit. The gas flow rates into the system were adjusted to provide about 40% nitrous oxide in oxygen in the final mixture. In three animals, cardiac output and end-tidal and blood halothane concentrations using a gas chromatograph (Varian Aerograph Series 1200, Varian Associates, Palo Alto, California) were measured. Cardiac output was determined using 5% saline as the indicator and a flow-through conductivity cell as the detector (Geddes, Peery and Steinberg, 1974). Arterial pressure and lead II e.c.g. were recorded in all animals.

RESULTS

Table I summarizes the anaesthetic procedures and figure 3 presents a typical record of events obtained.
**Table I. Anaesthetic procedures.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Species</th>
<th>Wt. (kg)</th>
<th>Anaesthetic agent</th>
<th>Duration (hr)</th>
<th>Delivery rate of anaesthetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.6.73</td>
<td>Horse</td>
<td>545</td>
<td>Methoxyflurane</td>
<td>2</td>
<td>50 x 8 = 400</td>
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<tr>
<td>21.6.73</td>
<td>Horse</td>
<td>455</td>
<td>Halothane</td>
<td>2</td>
<td>26 x 28 = 728</td>
</tr>
<tr>
<td>28.7.73</td>
<td>Horse</td>
<td>455</td>
<td>Halothane</td>
<td>3</td>
<td>30 x 12 = 360</td>
</tr>
<tr>
<td>14.3.73</td>
<td>Pony</td>
<td>182</td>
<td>Halothane</td>
<td>3</td>
<td>20 x 5 = 100</td>
</tr>
<tr>
<td>11.4.73</td>
<td>Pony</td>
<td>149</td>
<td>Halothane</td>
<td>3</td>
<td>16 x 7 = 112</td>
</tr>
<tr>
<td>30.3.73</td>
<td>Pony</td>
<td>123</td>
<td>Halothane</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>16.10.73</td>
<td>Calf</td>
<td>155</td>
<td>Halothane</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>15.10.73</td>
<td>Calf</td>
<td>132</td>
<td>Halothane</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>21.2.73</td>
<td>Sheep</td>
<td>68</td>
<td>Halothane</td>
<td>1</td>
<td>24 x 24 = 576</td>
</tr>
<tr>
<td>25.6.73</td>
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<td>60</td>
<td>Halothane</td>
<td>1</td>
<td>36 x 12 = 432</td>
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<tr>
<td>26.6.73</td>
<td>Pig</td>
<td>107</td>
<td>Halothane</td>
<td>1</td>
<td></td>
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<tr>
<td>13.2.73</td>
<td>Dog</td>
<td>28</td>
<td>Halothane</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>14.2.73</td>
<td>Dog</td>
<td>19</td>
<td>Halothane</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>20.2.73</td>
<td>Dog</td>
<td>19</td>
<td>Halothane</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>27.2.73</td>
<td>Dog</td>
<td>14</td>
<td>Halothane</td>
<td>1</td>
<td></td>
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<tr>
<td>18.2.73</td>
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<td>18</td>
<td>Halothane</td>
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<td>Halothane</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>17.7.73</td>
<td>Dog</td>
<td>12</td>
<td>Halothane</td>
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<td>18 x 8 = 144</td>
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<td>18.7.73</td>
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<tr>
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<td>Halothane</td>
<td>4</td>
<td></td>
</tr>
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<td>5.11.73</td>
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<td>25</td>
<td>Halothane</td>
<td>6</td>
<td>10 x 4 = 40</td>
</tr>
<tr>
<td>6.11.73</td>
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<td>20</td>
<td>Halothane</td>
<td>6</td>
<td>11 x 5 = 5</td>
</tr>
<tr>
<td>7.11.73</td>
<td>Dog</td>
<td>20</td>
<td>Halothane</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>8.11.73</td>
<td>Dog</td>
<td>18</td>
<td>Halothane</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>12.11.73</td>
<td>Dog</td>
<td>20</td>
<td>Methoxyflurane</td>
<td>4</td>
<td>12 x 11 = 132</td>
</tr>
<tr>
<td>14.11.73</td>
<td>Dog</td>
<td>19</td>
<td>Chloroform</td>
<td>4</td>
<td>13 x 8 = 104</td>
</tr>
</tbody>
</table>

*Vd*= Drop size (µl/drop), measured by counting the number of drops falling into a graduated container to provide a volume of 2 ml.

From a dog during halothane anaesthesia. Respired gas and blood halothane concentrations are shown at the top of the illustration; cardiac output and arterial pressure are shown below and at the bottom is shown the rate of delivery of halothane, expressed as microlitres of liquid per min, determined by multiplying drop size by drop rate.

At about 140 min in the example shown in figure 3, the delivery of halothane was increased and the blood concentration increased correspondingly. As the blood halothane concentration increased, both cardiac output and arterial pressure decreased. For the next 30 min the arterial pressure reflected the rapid changes in the inspired concentration of halothane. When delivery of the halothane was discontinued at 170 min, arterial pressure and cardiac output began to increase, the former showing the most rapid recovery.

**DISCUSSION**

This preliminary study has shown that it is possible to use ultrasound to vaporize anaesthetic liquids and maintain the desired depth of anaesthesia. There are several outstanding features of this method, the most attractive of which is ease of control. For example, the ultrasonic generator can vaporize large quantities of the anaesthetic rapidly. The model used in this study had the capability for vaporizing more than 3 ml of anaesthetic liquid per min. It should be obvious that the delivery rate is continuously controllable from this maximum down to zero. Another feature of this system is the lack of need for additional carrier gases to transport the anaesthetic vapour. The vaporizer can be placed directly in the airway and offers very little resistance to respiratory air flow. In addition, intermittent positive pressure ventilation does not alter the vaporization rate.

Because neither heat nor pressure is used to achieve vaporization, anaesthetic vapours can be produced easily over the broadest range of environmental temperatures, independent of ambient pressure. A most valuable feature of the ultrasonic method is its applicability to studies involving a variety of anaesthetic agents and subject sizes. As a research tool, ultrasonic energy allows investigation of anaesthetic substances which are difficult to vaporize and at present are little used. In this
The study the same vaporizer was used with three different anaesthetic agents and on animals ranging in weight from 12 to 545 kg.

Mention should be made of the vapour particle size. Although no measurements were carried out, it is known that with ultrasonic vaporization, the particle size is dependent upon the frequency of the ultrasound and surface tension. In this study a frequency of 1.5 mega-Hz was employed and it is estimated that the vapour particles were about 5 μm in diameter. Herzog, Norlander and Engstrom (1964) reported that the use of a 3 mega-Hz ultrasonic nebulizer provided water vapour particles 0.8–1 μm in diameter and Christoforidis, Tomashefski and Mitchell (1971) reported that 1.3 mega-Hz provided water vapour particles 6.2 μm in diameter. In the present study it is important to recognize that the vapour particles are of a volatile anaesthetic liquid and, in all probability, are quickly converted into the gas phase in the warm respiratory tract. It is also to be noted that the ultrasonic vaporizer used in this study was originally designed for use with water to produce a mist. For vaporization of anaesthetic liquids a slightly higher ultrasonic frequency (3.5 mega-Hz) would provide a smaller particle size which may be preferable.

It has been reported that, in patients with obstructive respiratory disease, the use of ultrasonically nebulized water results in an increase in airway resistance (Cheney and Butler, 1970; Malik and Jenkins, 1972). However, the same authors reported essentially no change in airway resistance in normal subjects. It must be noted that, in these studies, comparatively large volumes of water were vaporized. In the present study, comparatively small volumes of anaesthetic liquids were used, and, although airway resistance studies were not performed, there was no clinical evidence of increased airway resistance.

In conclusion, no unusual events accompanied the use of ultrasound to vaporize the three anaesthetic agents used in this study. The characteristics of the anaesthesia, as judged from clinical signs, were indistinguishable from those of anaesthesia obtained when using conventional vaporizers.

ACKNOWLEDGEMENT
The authors wish to acknowledge the assistance of Cleafe Best, Chief Scientist, and Dr Dennis Bruner of the Monaghan Co. for their assistance in providing much of the hardware employed in this study. We also wish to acknowledge the assistance of Drs J. D. McCrady and M. Bailey, of the Texas A. & M. College of Veterinary Medicine, for the use of the large-animal facilities. The study was supported in part by the Monaghan Co., Littleton, Colorado.

REFERENCES
VAPORIZING ANAESTHETICS BY ULTRASONIC ENERGY

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L'EMPLOI DE L'ENERGIE ULTRASONIQUE
POUR VAPORISER LES LIQUIDES
ANESTHESIQUES

RESUME
L'énergie ultrasonique telle qu'elle est fournie par un
vaporisateur d'eau en vente dans le commerce a été
employée pour vaporiser le méthoxyflurane, l'halothane
et le chloroforme. Le vaporisateur était placé directement
dans le conduit respiratoire et le liquide anesthésique
était vaporisé goutte à goutte. L'anesthésie a été maintenue
pendant des périodes dont la durée maximale était
de 6 h chez des chevaux, des poneys, des veaux, des
moutons, des chiens et un porc. Cette méthode de
vaporisation de liquide est applicable pour toutes sortes
d'anaesthésiques. Elle est facile à réguler et il est possible
d'utiliser le même vaporisateur pour des sujets de tailles
très diverses. Le vaporisateur peut être placé directement
dans le circuit respiratoire et n'offre pratiquement aucune
résistance à la respiration.

DIE VERWENDUNG VON
ULTRASCHALLENERGIE ZUR VERDAMPFUNG
ANÄSTHETISCHER FLÜSSIGKEITEN

ZUSAMMENFASSUNG
Ultraschallenergie, erzeugt durch einen im Handel
erhältlichen Wasserverdampfer, wurde zur Verdampfung
von Methoxyfluran, Halothan und Chloroform
verwendet. Der Verdampfer wurde direkt in die Atmungs-
leitung eingeschaltet, und die Narkoseflüssigkeit wurde
tropfenweise verdampft. Bei Pferden, Ponies, Kälbern,
Hunden und bei einem Schwein wurde die Narkose für
Perioden von bis zu 6 Stunden aufrechterhalten. Diese
Methode der Flüssigkeitsverdampfung ist auf eine große
Vielfalt von Narkosemitteln anwendbar. Sie ist einfach
kontrollierbar, und derselbe Verdampfer kann bei Sub-
jekten von sehr verschiedener Größe verwendet werden.
Der Verdampfer kann direkt in den Atmungskreislauf
eingesetzt werden und bedeutet praktisch keinen Wider-
stand für die Atmung.

EMPLEO DE ENERGIA ULTRASONICA PARA
VAPORIZAR LIQUIDOS ANESTESICOS

SUMARIO
Se empleó la energía ultrasonica proporcionada por un
vaporizador de agua, disponible en el comercio, para
vaporizar metoxiflurano, halotano y cloroformo. Se colocó
el vaporizador directamente en el conducto respiratorio
y se vaporizó líquido anestésico gota a gota. La anestesia
se mantuvo por períodos superiores a 6 horas en caballos,
ponies, terneros, ovejas, perros y un cerdo. Se puede
aplicar este método de vaporizar líquidos a una extensa
variedad de anestésicos. Es fácil de controlar y se puede
utilizar el mismo vaporizador para gran número de
sujetos diferentes. Se puede colocar el vaporizador direc-
tamente en el circuito respiratorio sin ocasionar ninguna
dificultad en la respiración.