Performance Characteristics of Conventional and Prototype Humidifiers and Nebulizers*


The output of water from conventional and experimental humidification devices was determined under conditions similar to those encountered by a patient who is intubated and spontaneously breathing. Absolute humidity was measured by a modified dewpoint hygrometer, and relative humidity at 37°C was then calculated. Only two of the unheated pneumatic nebulizers tested were capable of delivering near 100 percent relative humidity at 37°C, while both ultrasonic nebulizers tested were able (at maximum outputs) to more than double this humidity content. An external heat source was necessary to increase the water content of gases delivered from pure humidifiers (no particulate water output) to above 50 percent relative humidity at 37°C. No correlation could be made between visible fog and actual water content in the humidified gases. Frequent changes in control were necessary to maintain a constant output when the heated humidifier was run continuously for a six-hour period, while prolonged warm-up periods were necessary prior to achieving stable outputs when the ultrasonics were so tested. The most efficient unheated pneumatics, however, maintained a stable and satisfactory output throughout the six-hour test period. It was concluded that the newer pneumatically driven, unheated nebulizers are capable of delivering gases with nearly 100 percent relative humidity at 37°C, therefore eliminating the need for heated or ultrasonically driven nebulizers for routine clinical use.

The human respiratory tract is remarkably efficient in filtering, humidifying, warming, and, in general, air-conditioning inspired gas. While the nose and mouth primarily perform these functions, even when they are bypassed, as with an endotracheal tube, the warming and humidification of inspired gas are essentially completed by the second or third tracheal bifurcation.1,2

During periods of environmental or disease-induced stress, the airways and their linings are subjected to conditions that make their continued patency difficult. Maintenance of an optimum environment in which the mucociliary escalator may continue to mobilize the secretions is imperative. Although pulmonary secretions can theoretically become so thin that mobilization is impaired, increased viscosity with drying and inspissation is a far more common cause of pulmonary dysfunction.

Thus, when therapeutic gas mixtures that have an essentially zero water content are delivered to a patient who has pulmonary disease, water should be added to the inspiratory gas. Whether this added water should be in vapor or particulate form, or whether it should be heated or unheated, is still debatable.

The more basic questions are: What is the actual output of water of commercially available nebulizers? Are nebulizers stable during prolonged use? Further, since airway burns can occur with heated water particles and vapors,3 and excess water has been reported to have caused deterioration in pulmonary function,4,5 determination of the output of various nebulizers and vaporizers is important. We determined these parameters with the use of a modified dewpoint hygrometer. Similar, direct quantita-

*From the Departments of Anesthesiology and Chemical Engineering, the University of Florida, Gainesville.
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Reprint requests: Dr. Klein, Department of Anesthesiology, University of Florida College of Medicine, Gainesville 32610
tive studies in the past have required the use of the mass spectrophotometer, and have not evaluated the newer pneumatic nebulizers or heated pneumatic nebulizers, in general which are commonly used during spontaneous ventilation with a T-tube or Briggs adapter system.

**Methods**

Nebulizer and humidifier outputs were determined for the equipment listed in Table 1. Absolute humidity was determined from the dewpoint, as measured on a dewpoint hygrometer (Model 880, Cambridge Systems Inc.). The dewpoint, which is the temperature at which a gas sample possesses 100 percent relative humidity, thus permits the calculation of relative humidity at any given temperature. Relative humidity at 37°C (RHBT) was then calculated by the following formula:

\[
\text{Relative humidity (percent) at } 37°C = \frac{\text{vapor pressure of water at measured dewpoint}}{\text{vapor pressure of water at } 37°C} \times 100
\]

The experimental model is illustrated in Figure 1. All devices were powered with oxygen from a standard 50 PSI power source. (The Hydro-Sphere™ nebulizer was also powered by the air compressor supplied by the factory.) A 6-foot by 3-inch corrugated plastic delivery tube was connected to the nebulizer or humidifier to be studied. A T-connector and reservoir tube were attached distally to the corrugated tube. Sampling was then done continuously through the patient’s inspiratory port of the T-tube. The reservoir tube was utilized to prevent room air admixture with the gas which was to be sampled and analyzed. Thus, the test system was similar to that which is used in clinical practice during spontaneous ventilation in a patient who has an endotracheal tube in place.

Samples of gas were drawn from the T-tube port by means of a suction pump at a continuous aspiration rate of 1.5 to 2.0 standard cubic feet per hour. The temperature of the sample

| Equipment Evaluated, Mode of Operation and Conditions under Which Study Was Performed |
|----------------------------------------|-------------------|------------------|-------------------|
| Humidifier                            | Type              | Nebulizer        | Type              | Comments                                      |
| Ohio Deluxe Nebulizer                 |                   | X                | Bernoulli effect  | Studied at 40%, 60%, and 100% O₂              |
| Ohio Medical Products                 |                   |                  |                   |                                               |
| Aqua Pac 500 ml Humidifier            | X                 | Bubbler          |                   |                                               |
| Respiratory Care, Inc                 |                   |                  |                   |                                               |
| Bird 500 ml Inline Micro-nebulizer    | X                 | Bubbler          | Bernoulli effect  |                                               |
| Bird Corporation                      |                   |                  | with ball impactor|                                               |
| Bennett Cascade Humidifier            | X                 | Bubble Diffuser  |                   |                                               |
| Puritan-Bennett Corporation           |                   | Gas Pass Over    |                   |                                               |
|                                       |                   | Heated           |                   |                                               |
| DeVilbiss Ultrasonic                  | X                 | Ultrasound       |                   | Blower attachment not utilized. External gas |
| Nebulizer, Model No. 35               |                   |                  |                   | source used to deliver mist                  |
| DeVilbiss Company                     |                   |                  |                   |                                               |
| Hudson Humidifier/Nebulizer           | X                 | Bubbler          | Bernoulli effect  |                                               |
| Model 3210 Hudson Company             |                   |                  |                   |                                               |
| Hydro-Sphere Nebulizer                | X                 | Ruptured film    |                   |                                               |
| Owens-Illinois Corp                   |                   | with ball impactor|                   |                                               |
| Ideal Humidifier/Nebulizer            | X                 | Bubbler          |                   |                                               |
| Ideal Plastics Corp                   |                   |                  |                   |                                               |
| McGaw Humidifier                      | X                 | Cascade Bubbler  |                   |                                               |
| McGaw Laboratories                    |                   |                  |                   |                                               |
| Mist O₂ Gen Nebulizer                 | X                 | Ultrasonic       |                   | External gas source not used. Internal       |
| Mist O₂ Gen Equipment Co              |                   |                  |                   | blower used to deliver mist                   |
| Puritan Bubble/Jet                    | X                 | Cascade Bubble   |                   |                                               |
| Puritan-Bennett Corp                  |                   | Diffuser         |                   |                                               |
| Puritan Nebulizer                     | X                 | Bernoulli effect |                   | Studied at 40%, 70%, and 100% O₂             |
| Puritan-Bennett Corp                  |                   |                  |                   |                                               |
| U-Mid-Hi Nebulizer                    | X                 | Bernoulli effect |                   |                                               |
| Bard Parker                           |                   |                  |                   |                                               |
| Universal Humidifier/                 | X                 | Bubbler          |                   |                                               |
| Nebulizer                             |                   |                  |                   |                                               |
| Air Products and Chemicals, Inc       |                   |                  |                   |                                               |

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of gas was noted by means of a mercury thermometer or a freshly calibrated metal Bennett thermometer located at the patient inspiratory port. Between the sampling port and the hygrometer, the sample was heated by passing it through a copper coil (8 feet in length by ⅛-inch internal diameter with a diameter coil of 4 inches), which was submerged in a water bath at a temperature of 85°C. The temperature of the sample gas is thus sufficiently elevated so that vaporization occurs and all particulate water is converted into molecular water, i.e., water vapor. A heating element was used to maintain increased gas temperatures in the sampling tube that was not exposed to the waterbath, and also to increase the temperature of the mirror assembly of the hygrometer according to suggestions by the manufacturer. The temperature of the mirror assembly was kept at approximately 50° to 55°C.

Dewpoint determinations are made on gas samples which were produced by flowing oxygen at incremental levels, generally up to 15.0 L/min through the nebulizer or humidifier. The temperature of the water bath, length of the heated coil, the method of introduction of the mist sample, and all other physical conditions were maintained constant throughout the study. The hygrometer was balanced prior to beginning evaluation of each device. The relative humidity that is reported reflects a steady state value which occurred over a four- to six-minute period following the change of variables.

The dewpoint determinations were taken at one gas sample flow rate, and at various oxygen flow rates for the different devices tested, except for the Mistogen ultrasonic nebulizer, which has no calibration for flow rates when the built-in blower is utilized. The readings in this case were taken at different switch positions (power supply), as indicated in the table for ultrasonic nebulizers.

All pneumatic nebulizers were tested when run at room temperature (25°C). Some, however, as noted, also were heated until an inlet temperature (patient inspiratory port) of 37°C was maintained.

**RESULTS**

Bubble humidifiers consistently had a low output of water. The highest output (38 to 48 percent RHBT) was found at the lowest flow rate (2.5 L/min). There was a linear decrease in relative humidity in all humidifiers tested as flow rates were increased.

**Graph**

Figure 2. Humidity output of six unheated humidifiers with increasing oxygen flow rate. Note that efficiency declines rapidly as gas delivery is increased.

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increased from 2.5 to 10 L/min (Fig 2).

Pneumatically driven nebulizers varied considerably in their water output (Fig 3). Only two of the devices tested at room temperature yielded outputs above 75 percent saturation at 37°C; the Ohio Deluxe and the Owens-Illinois Hydro-Sphere. Other nebulizers (Puritan and Hudson) employing the Bernoulli effect, without modification by an impacting anvil, showed decreasing saturation as flow rates increased above 8 to 10 L/min. The Hydro-Sphere, however, within the limits tested, showed increasing output as driving gas flows increased to a maximum of nearly 100 percent saturation at body temperature, even though neither the gas flow nor the water were heated above room temperature (Fig 3). There was no difference in the pattern of output of this unit, whether it was powered by oxygen flow or the air compressor (Fig 4).

Heating the reservoir of water significantly increased the output of the two nebulizers and one humidifier so tested (Fig 5). The Bird 500 ml in-line nebulizer increased its output to 100 to 110 percent saturation at 37°C, while the Ohio Deluxe when heated to maintain a sampling port temperature of 37°C, increased its output to 120 to 140 percent saturation at 37°C. The Bennett Cascade humidifier was found to be highly temperature-sensitive, but flow-insensitive. All heated devices caused major condensation and rain-out of water as the output cooled from reservoir temperature to 37°C along the unheated delivery tube.

The two ultrasonic nebulizers tested delivered supersaturated gas at maximum settings (Fig 6). However, at lower output settings and prior to warm up they, too, delivered far less than 100 percent saturation at body temperature, despite the fact that they produced a visibly dense fog.

When the DeVilbis 35 ultrasonic nebulizer and the Bennett Cascade humidifier were tested over a six-hour period, output changes during the warm-up period become obvious (Fig 7). Figure 7 shows that, while a switch setting of No. 3 on the ultrasonic nebulizer will produce a fog with 115 percent relative humidity at 37°C, it required nearly
three hours to achieve this steady state. When the
Hydro-Sphere and Ohio Deluxe nebulizers were
run continuously for a six-hour period, essentially no

Figure 7. Delay is required to achieve stable water output
with both the ultrasonic nebulizer and Cascade humidifier.
(DeVilbiss 35 was held at a constant No. 3 power setting while
the Bennett Cascade required frequent changes in heater
temperature throughout test periods.) Contrast this to the
prompt stability in output from the Hydro-Sphere
and Ohio Deluxe. Gas flow rates were 10 L/min with all
devices.

Figure 8. Increased water production occurs with increased
dyspnea flow at specified power settings.

fluctuation in output occurred. Difficulty in achiev-
ing a constant humidity from the Cascade humidifier
also can be seen during the first 60 minutes of
operation. Although consistency was achieved from
one to six hours of running the Cascade, frequent
adjustments in the temperature rheostat of the heating
element were necessary to maintain the sampling port gas in a steady state of temperature and humidity.

Further evaluation of the DeVilbiss ultrasonic
nebulizer at less than maximum output settings
showed a near linear increase in absolute water output
when settings were increased and as oxygen
flow was increased through the chamber (Fig 8).
However, when this same data is plotted in a differ-
ent manner (Fig 9), it becomes obvious that water
content per unit of gas can vary by as much as 80
percent.

Discussion

While there is general agreement that inspired
medical gases should be humidified,7-9 no one has
conclusively demonstrated how much humidity is
optimal. This and other studies have shown that the
amount of humidification added to inspired medical
several reports suggested that excessive water in inspired gas may be deleterious.\textsuperscript{4,5,12,13} The use of heaters in nebulizers and humidifiers as a technique to increase water output, creates several problems. In addition to being unstable and difficult to maintain at a constant temperature and output, they also present a potential hazard. In the companion paper, we reported a case of frank tracheal burns due to excessive temperatures of inspired, humidified gases,\textsuperscript{8} while others\textsuperscript{14,15} have elucidated the mechanics of systemic heat retention during breathing of heated, wet gases.

In an attempt to visually assess the adequacy of nebulizer output during mist therapy, fog density has been discussed.\textsuperscript{16} In this study, however, we were unable to quantitate the actual amount of water present by observing the output of fog or its density. What appeared to be an extremely dense fog often revealed a saturation of only 50 percent to 60 percent at 37°C.

Benson and Graff\textsuperscript{14} have suggested that 100 percent saturation at 32°C is optimum for inspired gases and that conventional unheated nebulizers cannot meet this demand. Although both the unheated Ohio Deluxe and Hydro-Sphere met and modestly exceeded this water output in our study, we found several difficulties in achieving and maintaining even this arbitrary endpoint with other systems. They included: 1) heated systems are not stable and outputs change with time, reservoir levels, and flow rates; 2) changes in driving gas flow rate alter the efficiency in most systems; and 3) changes in reservoir levels, temperature within the reservoir (even in some unheated systems), and plugging of the Bernouilli jets caused output changes during prolonged operation in nearly all systems, and achieving a true, steady state was extremely difficult.

We conclude that newer, unheated, pneumatic nebulizers, such as the Hydro-Sphere and Ohio Deluxe, do provide stable outputs of humidified gas for prolonged periods when compared to other types of equipment studied. It is important to point out that these studies were conducted at constant gas flows in a system mimicking spontaneous T-tube ventilation, and that they may not be comparable to the intermittent gas flows that occur with mechanical ventilation. Further studies are obviously necessary to determine what levels of humidification are optimal to prevent both under- and overhydration of patients.

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