Performance Characteristics of Conventional and Prototype Humidifiers and Nebulizers*

E. F. Klein, Jr., M.D.; Dinesh A. Shah, Ph.D.; N. J. Shah, B.S.; Jerome H. Modell, M.D., F.C.C.P.; and Dave Desautels, A.R.I.T.

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 humudity 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.
Supported in part by a grant from Owens-Illinois and from National Institutes of Health GM1746-04.
Manuscript received February 1; revision accepted May 25.
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,[6] 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:

$$\text{Relative humidity (percent) at } 37^\circ\text{C} = \frac{\text{vapor pressure of water at measured dewpoint}}{\text{vapor pressure of water at } 37^\circ\text{C}} \times 100$$

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 ⅞-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

Table 1—*Equipment Evaluated, Mode of Operation and Conditions under Which Study Was Performed*

	Humidifier	Type	Nebulizer	Type	Comments
Ohio Deluxe Nebulizer Ohio Medical Products			X	Bernouilli effect with ball impactor	Studied at 40%, 60%, and 100% O_2
Aqua Pac 500 ml Humidifier Respiratory Care, Inc	X	Bubbler			
Bird 500 ml Inline Micro-nebulizer Bird Corporation			X	Bernouilli effect with ball impactor	
Bennett Cascade Humidifier Puritan-Bennett Corporation	X	Bubble Diffuser Gas Pass Over Heated			
DeVilbiss Ultrasonic Nebulizer, Model No. 35 DeVilbiss Company			X	Ultrasonic	Blower attachment not utilized. External gas source used to deliver mist
Hudson Humidifier/Nebulizer Model 3210 Hudson Company	X	Bubbler	X	Bernouilli effect	
Hydro-Sphere Nebulizer Owens-Illinois Corp			X	Ruptured film with ball impactor	
Ideal Humidifier/Nebulizer Ideal Plastics Corp	X	Bubbler			
McGaw Humidifier McGaw Laboratories	X	Cascade Bubbler			
Mist O_2 Gen Nebulizer Mist O_2 Gen Equipment Co			X	Ultrasonic	External gas source not used. Internal blower used to deliver mist
Puritan Bubble/Jet Puritan-Bennett Corp	X	Cascade Bubble Diffuser			
Puritan Nebulizer Puritan-Bennett Corp			X	Bernouilli effect	Studied at 40%, 70%, and 100% O_2
U-Mid-Hi Nebulizer Bard Parker			X	Bernouilli effect	
Universal Humidifier/ Nebulizer Air Products and Chemicals, Inc	X	Bubbler			

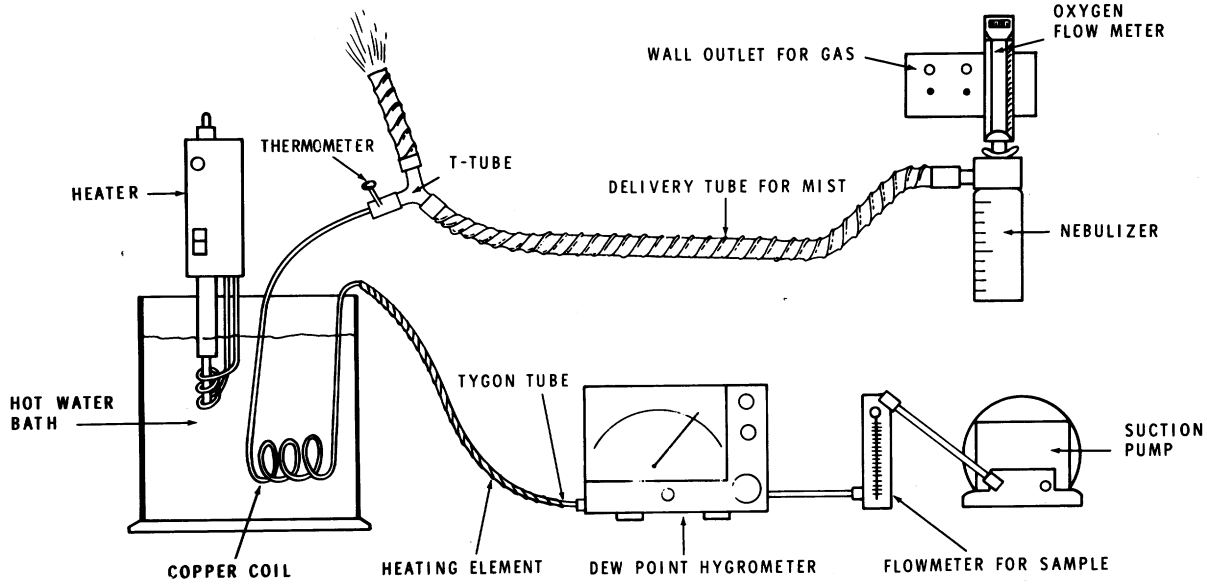

FIGURE 1. Schematic diagram of experimental apparatus used in study. Note that the reservoir tube is placed distal to T-connector to prevent admixture of room air with test gas.

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, *ie*, 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

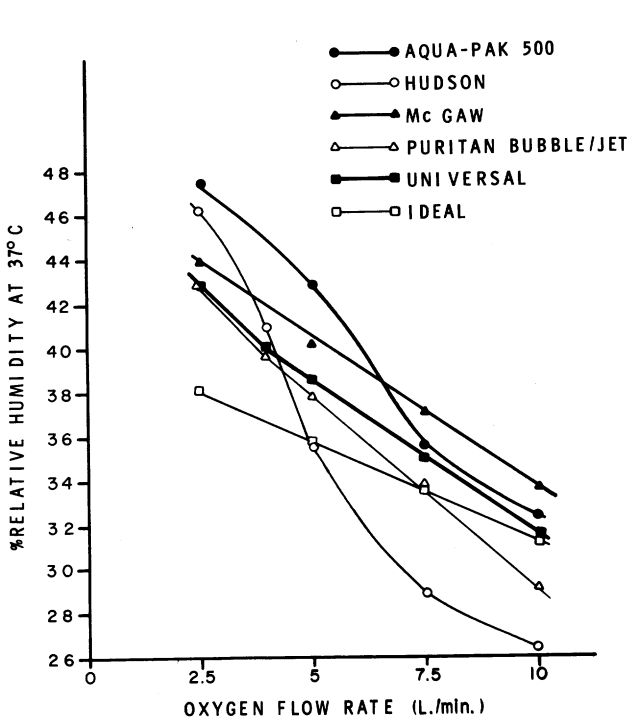

FIGURE 2. Humidity output of six unheated humidifiers with increasing oxygen flow rate. Note that efficiency declines rapidly as gas delivery is increased.

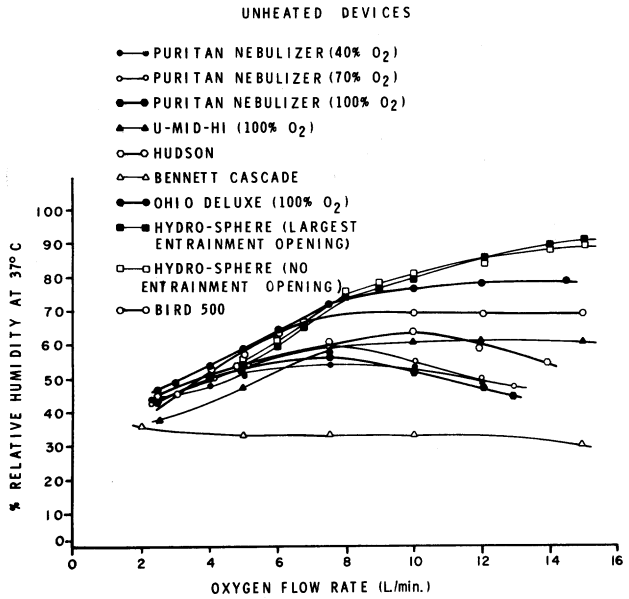

FIGURE 3. Humidity output of unheated devices as related to oxygen flow rates. The Bennett Cascade humidifier is included to illustrate the difference between unheated nebulizers and humidifiers.

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 Bernouilli 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

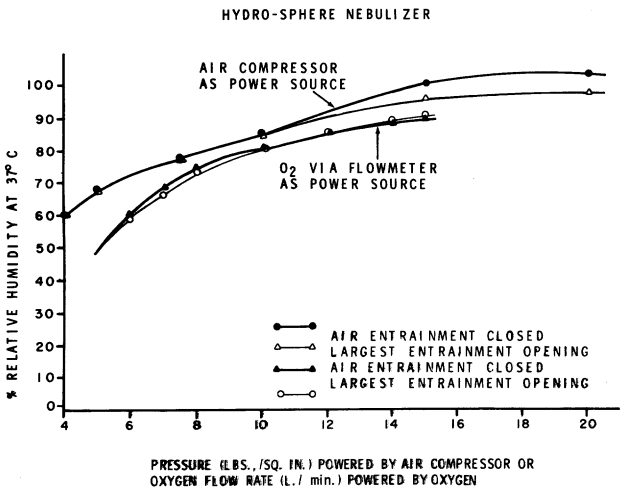

FIGURE 4. Humidity output of the Hydro-Sphere as a function of power source gas. Output curves are similar whether the air compressor or wall oxygen is utilized.

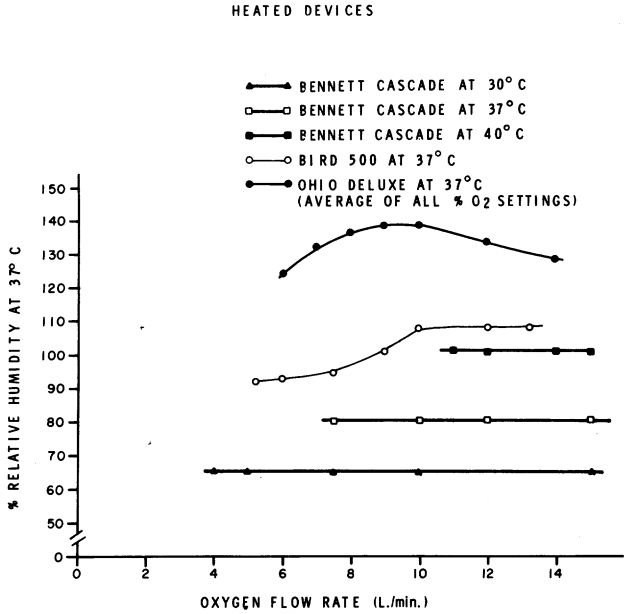

FIGURE 5. Initial flow rate listed for each piece of equipment is the minimum flow rate required to reach the desired temperature of the sample port. Note the increased humidity output with increased temperature, and compare the same devices at ambient temperature (Fig 3).

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 DeVilbiss 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

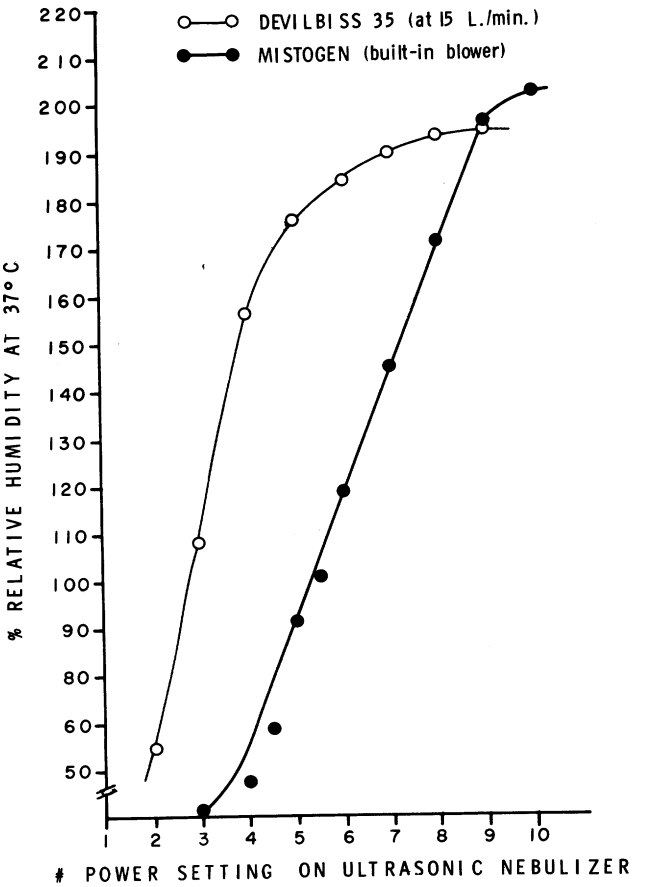

FIGURE 6. Increased water output of two of the ultrasonic nebulizers is critically related to power output. Note that even at mid-range power settings, supersaturated gas is delivered.

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

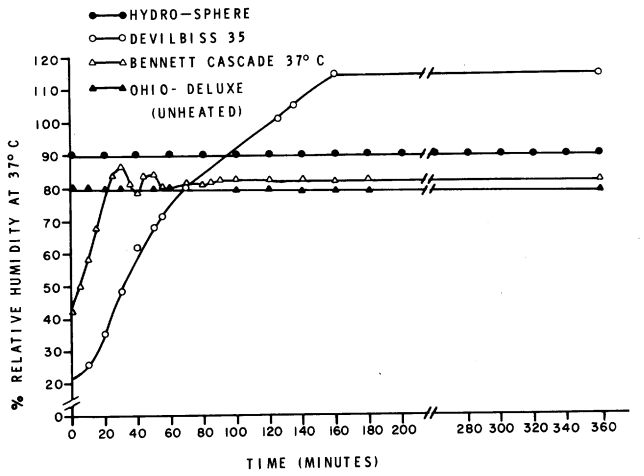

FIGURE 7. Delay is required to achieve stable water output with both the ultrasonic nebulizer and Cascade humidifier. (DeVilbiss 35 was held at a constant No. 3 power setting while the Bennett Cascade required frequent changes in heater temperature throughout test periods.) Contrast this to the prompt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

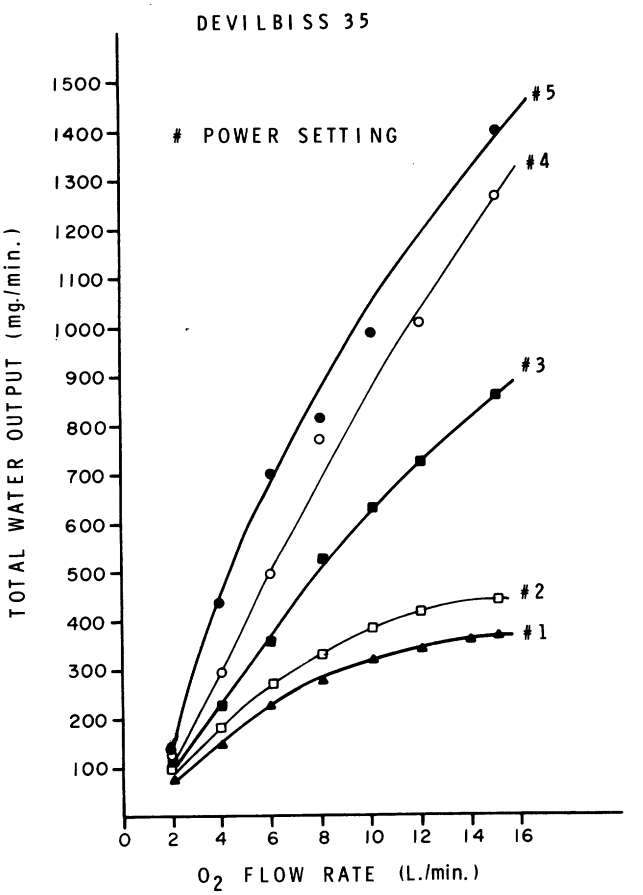

FIGURE 8. Increased water production occurs with increased oxygen flow at specified power settings.

fluctuation in output occurred. Difficulty in achieving 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 different 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

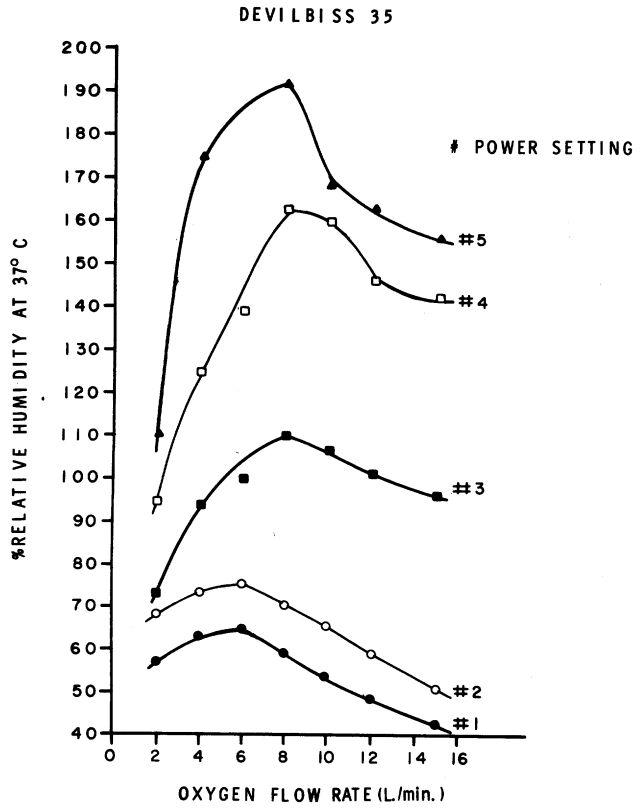

FIGURE 9. The percent increase in water production is less than the percent increase in driving gas flow. Thus, humidity content per unit gas volume decreases at higher flow rates.

gases by different types of clinical apparatus varies greatly. Bubble humidifiers seldom increase humidity significantly above that found in the average air-conditioned hospital ward, and their efficacy decreases rapidly as flow rates of gas increase. While this may be adequate when the upper airway is intact, it is obviously inadequate when a tracheostomy or endotracheal tube is in place. Ultrasonic nebulizers, on the other extreme, have been reported to have caused major water overloads[10-12] and pulmonary dysfunction[4,13] due to excessive amounts of water presented to the body via the respiratory tract. This study confirms the fact that large amounts of particulate water are produced by this type of nebulizer. Further, pneumatically driven nebulizers have extremely variable outputs and performance characteristics which are both flow and temperature dependent. The least efficient are little better than bubble humidifiers, while the most efficient are equivalent to the mid-range output settings of the ultrasonics. We also confirmed that heating elements improve the output performance of nebulizers, as well as humidifiers.

The general feeling that "the greater the output, the better the nebulizer" has prevailed in the medical community for the last several years. This concept has yet to be proved and, to the contrary, several reports suggested that excessive water in inspired gas may be deleterious.[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,[3] while others[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.[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[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.

REFERENCES

1 Dery R, Pelletier J, Jacques A, et al: Humidity in anaesthesiology. 3. Heat and moisture patterns in the respira-

tory tract during anaesthesia with the semi-closed system. Canad Anaesth Soc J 14:287-298, 1967
2 Dery R: Humidity in anaesthesiology. IV. Determination of the alveolar humidity and temperature in the dog. Canad Anaesth Soc J 18:145-151, 1971
3 Klein EF Jr, Graves SA: "Hot pot" tracheitis. Chest (in press)
4 Modell JH: Experimental studies in chronic exposure to ultrasonic nebulized aerosols. J Asthma Res 5:223-229, 1968
5 Modell JH, Giammona ST, Davis JH: Effect of chronic exposure to ultrasonic aerosols in the lung. Anesthesiology 28:680-688, 1967
6 Hayes B, Robinson JS: An assessment of methods of humidification of inspired gas. Br J Anaesth 42:94-108, 1970
7 Cushing IE, Miller WF: Considerations in humidification by nebulization. Dis Chest 34:388-403, 1958
8 Burton JDK, Lond MB: Effect of dry anesthetic gases on the respiratory mucous membrane. Lancet 1:235-238, 1962
9 Sara C, Currie T: Humidification by nebulization. Med J Aust 1:174-179, 1965
10 Herzog P, Norlander OP, Engstrom CG: Ultrasonic generation of aerosol for the humidification of inspired gas during volume-controlled ventilation. Acta Anaesth Scand 8:79-95, 1964
11 Harris RL, Riley HD Jr: Reactions to aerosol medication in infants and children. JAMA 201:953-955, 1967
12 Tamer MA, Modell JH, Rieffel CN: Hyponatremia secondary to ultrasonic aerosol therapy in the newborn. J Pediat 77:1051-1054, 1970
13 Modell JH, Moya F, Ruiz BC, et al: Blood gas and electrolyte determinations during exposure to ultrasonic nebulized aerosols. Br J Anaesth 40:20-26, 1968
14 Graff TD, Benson DW: Systemic and pulmonary changes with inhaled humid atmospheres: Clinical application. Anesthesiology 30:199-207, 1969
15 Rashad KF, Benson DW: Role of humidity in prevention of hypothermia in infants and children. Anesth Analg 46:712-718, 1967
16 Allan D: Proceedings of the Second Conference on Clinical Applications of the Ultrasonic Nebulizer. J Asthma Res 5:290, 1968