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Humidification during Positive-pressure Ventilation of Infants

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When the upper airway is bypassed for prolonged periods by an endotracheal or tracheostomy tube it is essential that means for adequate humidification of the inspired gas be provided. The intact upper airway normally warms the inspired gas to body temperature and saturates it with water.[1] Water content of the inspired mixture is approximately 44 mg/l when it enters the lower airway.

The heated humidifiers and ultrasonic nebulizers generally used with infant ventilators to provide this humidity have been less than satisfactory. To use an ultrasonic nebulizer properly it is necessary to calculate from minute ventilation the nebulization rate needed, and then to monitor the amount of water nebulized. Such measurements are impractical when ventilating infants because both the ventilatory volumes and the quantity of water needed are small. Adjustments for the contribution from the humidity of any ambient air used and for the loss due to fallout in the tubing are also necessary. Frequent measurements would be necessary because even at a fixed setting of the output control, the nebulization rate varies from time to time.[3,4] Finally, when low flows are passed through nebulizers modified for pediatric use to provide low outputs (*e.g.*, Bourns Modification of De Vilbiss Nebulizer Model 350 or 35) the nebulizers become so hot that much of the water is in the form of vapor rather than particles, in part explaining the excessive water deposited in the inspiratory tubing (unpublished observations).†

DEVELOPMENT OF A NEW HUMIDIFIER SYSTEM

For these reasons we consider that an ultrasonic nebulizer is inappropriate for use in mechanical ventilation of infants. Therefore, we have developed a suitable heated humidifier system. The design of such a system must take into consideration certain problems peculiar to the ventilation of infants. First, the volume of air within the system (humidifier and tubing) must be small, to avoid loss of tidal volume due to the compression of gas. Second, the use of small-bore tubing (as demanded by a low system volume) requires that condensation within the tubing be avoided. Finally, the gas must be saturated with water at body temperature when inspired. This is particularly difficult because of the rapid cooling along the tubing with the low minute volumes encountered in ventilating infants. This requirement can be satisfied by keeping the humidifier sufficiently hot to allow for such

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† These considerations may not apply fully when ventilators designed for adults are used for infants. Because of the large "compressible volume" the flow of gas through the humidifier is much larger than the infant's minute volume. This makes volume-limited operation impossible and makes even the estimation of tidal volume difficult.

cooling. However, we have determined that at a minute volume of 500 ml, with four feet of 5⁄16″ ID × ½″ OD silastic tubing at an ambient temperature of 75 F, the humidifier must be kept at 185 F for the inspiratory mixture to reach the patient saturated at 95 F. This is clearly unsatisfactory, because of both the huge amount of condensation inherent in such a system and the danger of a respiratory burn if the minute volume were to increase suddenly or if there were to be an accidental transfer of water from the humidifier to the infant.

We have designed a system which prevents the decrease in temperature in the inspiratory tubing, allowing the use of a humidifier heated to approximately body temperature. When the infant is nursed in an incubator which can be kept at or near body temperature, the simplest method is to mount the humidifier on the incubator and have the inspiratory tube enter the incubator without exposure to cooler ambient temperature or, even better, to keep the humidifier within the incubator. However, with a large infant or a newborn nursed outside an incubator, other methods must be devised. Insulation was tried and abandoned because of its bulk and because it did not permit the tubing to be inspected for condensation. Electrical heating tape was tried and abandoned because it is also bulky, opaque, and difficult to control and monitor. The device which we have developed and have used routinely for more than a year utilizes warm air to maintain the inspiratory tubing at the desired temperature.

The construction details are shown in figures 1 and 2. In brief, a heated bubbler humidifier was constructed from a Puritan heated nebulizer (the nebulizer cap was completely stripped of all parts concerned with nebulization and the resulting holes sealed with filled epoxy and silicone rubber [Dow 731]). A transformer (44) permits the temperature (36) of the exiting gas to be kept at 98–100 F. The thermostat (24) of the heater (23) is set to open at approximately 110–115 F as a safety measure. The inspiratory gases after leaving the humidifier reach the patient via a coaxial tube. The inner tube (38) which conveys the inspired mixture is 5⁄16″ ID silastic tubing. The outer tubing is lightweight transparent 1⅛″ OD reinforced corrugated tubing (14). Warm air from a hair dryer (8) is blown through the corrugated tubing to prevent the inspiratory gases from cooling. The distal temperature (18) of the air is adjusted to 105–120 F by varying the amounts of warm air permitted to leak out of the system. In practice the proper temperature can be achieved by allowing warm air to leak out of the 15-mm limb of a Wye adapter (11), which can be partially occluded with an endotracheal tube adapter to increase the distal temperature. Thus, condensation can occur only in the distal 6 to 8 inches of the silastic inspiratory tubing exposed to atmosphere.

Methods of Evaluation

The performance of the device was evaluated by measuring various temperatures within the unit using either calibrated mercury thermometers or hypodermic thermistor probes (Probe 524, Yellow Springs Instrument Co.).

Measurements were made at an ambient temperature of 75 F with the humidifier temperature (36) adjusted to 98 F and the distal hot air temperature adjusted to 105 or 120 F at various minute volumes. The temperature of the air stream was measured in the inspiratory tubing just proximal to the crosspiece (42) using a distensible rubber "artificial lung," and also during actual clinical use.

Results

The inspiratory gas temperature when it leaves the protection of the corrugated tubing was found to be the same as the exit temperature (18) of the warm air (105–120 F). Within one to two inches it cools to the temperature of the heated humidifier (36), that is, to its dew point, and condensation is seen. Cooling then continues more slowly at a rate of about 0.5 to 1.0 degree F/inch of tubing. The rate of cooling with the model was less at a higher minute volume (table 1). At minute volumes of 500 ml or more the inspiratory gas temperature is always greater than 90 F. Varying the exit temperature of the hot air from 105 to 120 F had little effect on the temperature of the inspiratory gas.

In clinical use the inspiratory gas temperature was measured on 50 occasions during ventilation of 15 infants. The inspiratory gas

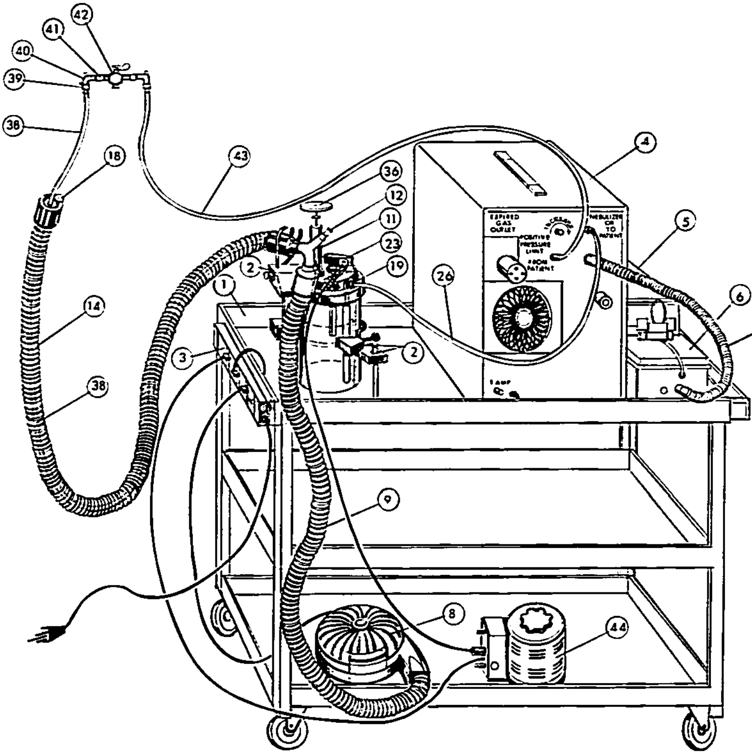

FIG. 1 (*above*) and FIG. 2 (*right*). The humidifier system and detail of humidifier.

1, Cart, Lakeside 526, Lakeside Mfg., Inc., Milwaukee, Wis.
2, Laboratory clamps, Fisher Scientific Co., Pittsburgh, Pa.
3, Outlet box, Waber 15CB-15, Waber Electronics, Inc.
4, Respirator, Bourns LS 104–150, Bourns, Inc., Riverside, Calif.
5, Oxygen analyzer, Beckman D2, Beckman Instruments, Inc., Fullerton, Calif.
6, Mix box, Bourns 51192-00201.
7, Corrugated tubing, Bourns P/N51569-00101.
8, Hair dryer, set to low, General Electric Co., HD 11, Bridgeport, Conn.
9, Hair dryer tubing.
10, Coupling, Bennett 3443, Puritan-Bennett Corp., Kansas City, Mo.
11, Wye, Bennett 0338.
12, Endotracheal tube adapter. Select size necessary to give temperature of 105 to 120 F at thermometer (18).
13, Molded rubber end, ⅞" ID, Collins P-503, Warren E. Collins, Inc., Braintree, Mass. Hole cut in side to admit elbow adapter (37) for inspiratory gas.
14, Reinforced transparent corrugated tubing, 1⅛" ID × 40" long, Collins P-502.
15, Holes for escape of hot air, ⅓" diameter.
16, Moulded rubber end 1⅜" ID, Collins P-505.
17, Molded insert to hold thermometer, Dow Medical Silastic 382 elastomer, Dow Corning Corp., Midland, Mich.
18, Thermometer, bimetallic, 60–120 F, 1" dial, Bennett 0893.
19, Humidifier cap, Bennett, 290-041, or 126-271 with all nebulization parts removed.
20, Gasket, Puritan 621015.

21, Gasket retainer ring, Puritan 612197.
22, Jar, Puritan 612070.
23, Immersion heater, Puritan 129-002.
24, Thermostat adjusting screw. Set for 110 F.
25, Molded silastic insert, Dow 382.
26, Tube, respirator to humidifier, silastic, 5/16" ID × 1/2" OD × 18" long, Dow 601-501.
27, Adapter, PVC 1/8" MIPT × 3/8" barb.
28, Coupling, Delrin, 1/8" FIPT × 0.557" OD × 1.74" long, glued into side port (29).
29, Side port of cap.
30, Adapter, elbow PVC, 1/8" MIPT × 3/8" barb.
31, Tube, silastic, 5/16" ID × 1/2" OD × 2" long, Dow 601-501.
32, Top part of cap.
33, Nipple, PVC, 3/8" MIPT × 2" long, glued into top port (32).
34, T, PVC, 3/8" FIPT.
35, Reducing bushing, PVC, 3/8" × 1/4" IPT.
36, Thermometer, bimetal, 20–240 F, Weston 2281-0015008, Weston Instruments, Inc., Newark, N. J.
37, Adapter, elbow, PVC, 3/8" MIPT × 3/8" barb.
38, Inspiratory tubing, silastic, 1/4" ID × 1/2" OD × 47" long, Dow 601-481.
39, Adapter, tracheostomy, size 8L, Bennett 3518L.
40, Elbow, Bennett 1025.
41, Coupling, silastic tubing 1/2" ID × 3/4" OD × 1" long, Dow 601-641.
42, T adapter with suction part, Bourns P/N 51339-00101.
43, Expiratory tubing, silastic, 5/16" ID, 1/2" OD × 72" long, Dow 601-501.
44, Variable transformer, Staco 3PN 1010, Staco, Inc., Dayton, Ohio. Adjust to give humidifier temperature of 96 F to 98 F (usual voltage is 35 to 45).

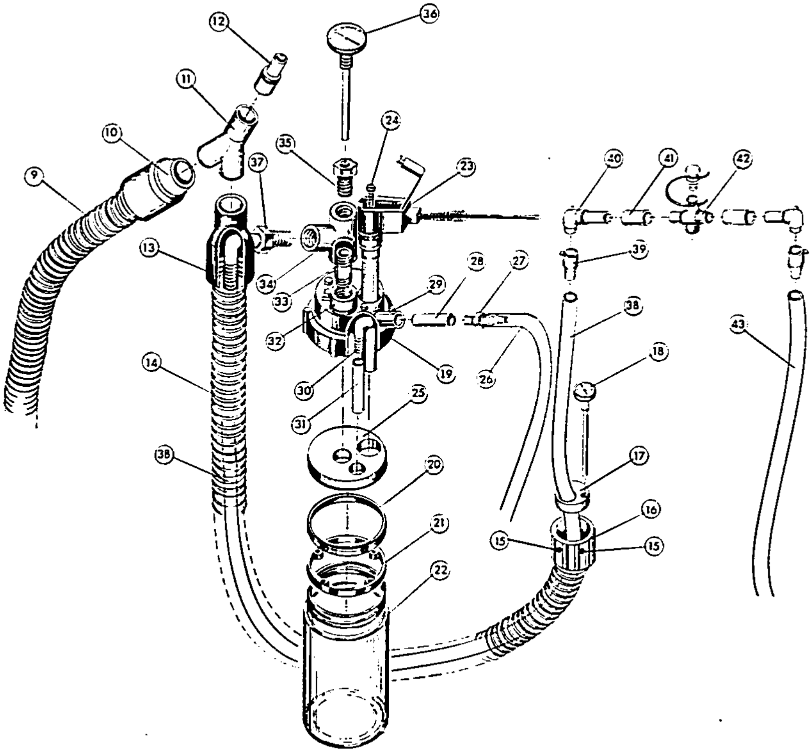

TABLE 1. Temperatures of "Inspired" Gas at Various Minute Volumes and Warm Air Temperatures with the Humidifier Set at 98 F

Rate (breaths/min)	Tidal Volume (ml)	Minute Volume (ml/min)	Temperature of Gas at Distal End of Inspiratory Tubing	
			Warm Air Exit Temperature 105 F	Warm Air Exit Temperature 120 F
35	143	5,000	98.0	98.0
100	50	5,000	97.5	98.0
30	100	3,000	97.0	97.5
100	30	3,000	97.0	97.0
20	50	1,000	93.0	93.5
50	20	1,000	93.5	93.5
20	25	500	90.0	90.0
50	10	500	90.0	90.0

temperature averaged 94 F, with a range of 89 to 97 F.

Discussion

These findings are predictable from the design. The gas leaves the humidifier saturated at body temperature. Within the coaxial tubing its temperature increases but its water content is unchanged. The water content is dependent on the humidifier temperature. The heat content of the inspiratory mixture is largely determined by its water vapor content rather than by its temperature, since the specific heat of the gas is small compared with the large latent heat of vaporization of water. Thus, in the distal exposed inspiratory tubing there is rapid cooling to the dew point, and the final inspiratory temperature is little affected by the warm air temperature. The temperature drop then depends upon the transit time of the gas and, therefore, is inversely related to the minute volume.

The humidifier system thus provides full saturation at approximately body temperature. We have used it for more than a year in conjunction with two Bourns ‡ respirators, and the adequate humidification has kept tracheal secretions fluid.

The system has been satisfactory in other respects. Its internal gas volume is low and the volume lost due to compression (when used with the Bourns respirator) is 0.4 ml/cm H_2O. This is less than that of the commercially available ultrasonic nebulizer system. The temperatures are stable and are generally reset only once a day when a new sterile setup is put in use. The entire system, except for the hair dryer, is sterilized at 145 F with ethylene oxide and aired for eight hours at 150 F.

Although the system was designed as a prototype only, it has proven durable enough for routine use, and six have been constructed. If the system should become commercially available, several refinements should be made. These include automatic control of temperature, automatic control of filling of the humidifier, suitable alarms, a brushless motor for the air blower, and improved packaging.

Summary

A new heated humidifier system which uses a humidifier at body temperature with the inspiratory tube kept warm by hot air to achieve the desired humidity without condensation is described.

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‡ When the humidifier system is used on the Bourns respirator a simple internal modification of the respirator is necessary. The tubing to the disconnect alarm and pressure gauge, normally connected to the inspiratory limb, should be rerouted and connected to the expiratory line to avoid an artifactually high recorded pressure due to the inspiratory line's being under water in the humidifier. Similar considerations might apply to other ventilators.