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A Comparison of Commercial Jet Nebulizers*

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Seventeen commercially available jet nebulizers from 15 commercial sources were studied (Acorn-I, Acorn-II, AquaTower, AVA-NEB, Cirrus, Dart, DeVilbiss 646, Downdraft, Fan Jet, MB-5, Misty Neb, PARI LC JET, PARI-JET, Salter 8900, Sidestream, Updraft-II, Whisper Jet). All nebulizers were filled with 2 ml of saline solution plus 0.5 ml of albuterol and powered with the same source (DeviJiss PulmoAide). We compared total output (TO), time for total output (TTO), and percent output in respirable range (PORR). The TO was obtained by weighing before nebulization and at the point of eightfold decline in output. The TTO was calculated from initiation of nebulization to the point of eightfold decline in output. The PORR was measured by a laser particle analyzer in continuous nebulization to the same point of abrupt drop in output. The TO varied from 0.98 to 1.86 ml (p<0.0001) with the Acorn-I, Acorn-II, Updraft-II, and Sidestream, significantly greater than the others (p<0.05). The TTO varied from 2.28 to 20.95 min (p<0.0001). The AquaTower, PARI LC JET and PARI-JET, DeVilbiss, and Dart were significantly shorter than the others (p<0.05). The PORR varied from 21.59 to 71.95 percent (p<0.0001). The Sidestream was significantly greater than all others (p<0.05). The PARI LC JET and PARI-JET were, in turn, significantly greater than the remaining models (p<0.05). To combine these characteristics, we calculated respirable particle delivery rate (RPDR) by dividing TO by TTO and multiplying by PORR. The RPDR varied from 0.03 ml/min to 0.26 ml/min (p<0.0001). The PARI LC JET (0.24 ml/min) and the PARI-JET (0.26 mg/min) had a RPDR that was significantly greater than the other models except the AquaTower, which, however, had a markedly variable performance. The Sidestream (0.19 mg/ml) did not differ significantly from the above group, nor from the DeVilbiss and Downdraft. All other models had significantly lower outputs (p<0.05). We conclude that the output characteristics of commercial nebulizers vary greatly and will impact on the time required for treatment as well as the total amount of drug delivered to the lungs.

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| MDI=metered-dose inhaler; PORR=respirable output; RPDR=respirable particle delivery rate; TO=total output; TTO=time for total output; VMD=volume mean diameter |

Key words: aerosol therapy; jet nebulizers

Inhaled medications for the treatment of asthma have become the mainstay of therapy. The principal means used to deliver inhaled particles are through jet nebulizers and fluorocarbon metered-dose inhalers (MDI). While the MDIs are more convenient,1 they cannot be used by young children and present problems to some individuals of all ages.2 Furthermore, there are impeding limits on the use of fluorocarbon-containing materials due to ozone depletion.3 The jet nebulizer may then gain even greater popularity.4

Many models of small-volume jet nebulizers are commercially available. Recommendations for medication doses by nebulizer treatment usually do not specify a particular model, suggesting a perception that they are functionally equivalent. There are, however, reports that suggest this is not true and that different models vary considerably in performance, including the rate and extent of delivery5-9 and the percent of output in the respirable range (<5 um).10-13 Furthermore, even within a single nebulizer model, there can be inconsistencies in unit performance.14,15

We report herein a study that was designed to explore the differences among the different models of reusable jet nebulizers commercially available in the United States at the time of the study. We examined, as well, the performance consistency by studying four units of each model. We demonstrated differences in volume output, time required to nebulize that volume, and in the percent of particles in the respirable range of 1 to 5 μm.16 The results of this study should allow clinicians to select nebulizers on the basis of demonstrated performance rather than solely on convenience and cost.

MATERIALS AND METHODS

Nebulizers

The 17 different nebulizers studied were the Acorn-I, Acorn-II, Fan Jet, Downdraft, and Whisper Jet (Marquest, Englewood, Colo), Aqua Tower (Medical Industries America, Adel, Iowa), AVA-NEB and Updraft-II (Hudson, Temecula, Calif), Cirrus (DHD Medical Products, Canastota, NY), Dart (Professional Medical Products, Greenwood, SC), DeVilbiss 646 (DeviJiss

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Health Care, Somerset, Pa), MB-5 (Mefar, Bovezzo, Italy), Misty Neb (Baxter, Valencia, Calif), PARI LC JET and PARI-JET (PARI Respiratory, Richmond, Va), Salter 8900 (Salter Labs, Arvin, Calif), and the Sidestream (Inspired Medical Products, Hopkinton, Mass). The nebulizers were studied using four units of each model, each run three times to determine intramodel and intermodel variability. All nebulizers studied were available in the United States. All were purchased through normal procurement channels to preclude special pretesting. All models were represented by the manufacturer to be reusable.

Volume Fill

Each nebulizer was filled with 2 ml of normal saline solution and 0.5 ml of albuterol (Proventil Nebulizer Solution, Schering Corp, Kenilworth, NJ). The initial and final weights were precisely determined on a balance (OHAUS Scale Corp, Florham Park, N J).

Testing Conditions

The driving pressure for the nebulizers was supplied by a compressor (DeVilbiss PulmoAide 5610D, DeVilbiss Health Care, Somerset, Pa) at ambient conditions, temperature of 20 to 23.8°C (68 to 75°F) relative humidity of 20 to 54 percent, and an elevation of 1.6 km (5,280 feet). This compressor, when not attached to a nebulizer, was determined to have a gas flow rate of 12.3 standard liters per minute. Nebulizer units were tested in random order.

Aerosol Characterization

The nebulizers were analyzed continuously with a high-volume scattering aerosol spectrometry probe (model CSASP-100, PMS, Boulder, Colo). The aerosol was analyzed for particles in the range of 0.5 to 32 μm. In this device, particles pass through a laser beam and the light bent or refracted. Larger particles refract light at a greater angle and are sized by their angle of refraction. When two particles pass through the laser beam at the same time or when a particle does not pass completely through the beam, the analyzer detects these events and excludes these data from calculation.

The probe was adapted for wet aerosol measurement with a separation device, employing the same negative pressure, which diverted part of the aerosol cloud to preclude overload with co-occurrence and oversizing of particles. Both the diverter and the suction system connected to the probe allowed for a flow rate of 16 L/min.

The suction accelerates particles through a parabolic horn and then through the sampling zone containing the laser. Sampling was performed over three different size ranges sequentially at an interval of 2 s. This allowed a complete measurement of the entire range every 6 s. Each of the three ranges of analysis contained 15 channels of increasing incremental size (0.5 to 8.0 μm at 0.5-μm increments; 1.0 to 16.0 μm at 1.0-μm increments, and 2.0 to 32.0 μm at 2.0-μm increments). There was overlap among ranges with the 0.5-μm increments being the most precise. A computer program automatically discarded the values from the channels in each range that overlapped with a more precise channel. This program also scaled the values from each range to 1.0-μm increments so that comparisons between ranges could be easily plotted. The program combined the particles from each similar channel for each time period analyzed and then converted the particle number into volumes by the formula \( V = \pi a^2 / 3 \). A volume distribution was determined by calculating the percentage of total volume in each size channel. From this profile, the percentage of total aerosol in the respirable range (1.0 to 5.0 μm) was calculated.

Time End Point

Nebulization was continued until an end point occurred that was represented by an eightfold drop in total number of particles read by the laser analyzer. This point correlated with the “sputtering point” of the nebulizers.\(^{3,17}\)

Variables Studied

1. Total Output (TO) in milliliters: This value was obtained by subtracting from the prenebulization weight the weight of the nebulizer at the point of eightfold drop in total particles (sputtering). The initial volume fill was 2.5 ml.
2. Time of Total Output (TTO) in Seconds: This value was the time required with continuous nebulization to reach the eightfold drop in nebulizer particle output.
3. Percent of Particles in the Respirable Range (PORR): This value was the mean of the percent of particles in the range of 1 to 5 μm during continuous nebulization to the point where the nebulizer output fell eightfold.
4. Respirable Rate (ml/min) (RPDR): This value gives weight to all three variables mentioned above. The TO was divided by the TTO and that number was multiplied by the PORR to yield the delivery rate per minute in the 1- to 5-μm range.

Statistical Analysis

Measurements of particle size were made in triplicate for each of the four units of each of the 17 commercially available nebulizers. For each outcome, the means were compared between nebulizers by one-way analysis of variance, and the variances were compared by Bartlett's test for homogeneity of variance. If the variances were significantly different at the 0.05 level, the means were compared using the Welch adjustment to the analysis of variance for unequal variances within groups. The individual nebulizers were compared using Fisher's Protected Least Significance Test at a level of \( p < 0.05 \). The results are summarized graphically using diamond plots, which are in the means and 95 percent confidence intervals about the means using a pooled estimate of the variance. All analyses were performed (using JMP Version 2.0.5) on a personal computer (Apple Quadra 700).

RESULTS

The results of the triplicate runs for four units of each of 17 models of jet nebulizers are summarized in Figures 1 through 4.

Volume

The TO to the point of eightfold decline in particle output for each of the 17 models of jet nebulizers is shown in Figure 1. Overall, both the means and variances were significantly different (\( p < 0.0001 \)) for each. The TO varied from 0.98 ml (Aquatower) to 1.86 ml (Sidestream). The TO of the Sidestream (1.86 ml) was significantly greater than all the others (\( p < 0.05 \)) and the TO of the Acorn I (1.63 ml), Acorn II (1.61 ml), and the Updraft II (1.62 ml) were significantly greater than the remainder (\( p < 0.05 \)). The TO from individual units of the AquaTower greatly varied.

Time

The time to the point of eightfold drop in particle output is shown in Figure 2. There was a highly significant difference among the means and variances
within the group (p<0.0001 for each). The TTO varied from 2.28 min (Downdraft) to 20.95 min (Acorn-II). The Downdraft (2.28 min), PARI-JET (2.39 min), AquaTower (2.47 min), and PARI LC JET (2.54 min) had total nebulization times that were shorter than those of the remaining models (p<0.05).

**Percent of Particles in Respirable Range**

The PORR is shown in Figure 3. There was a highly significant difference in the means and variances among the devices (p<0.0001 for means, p<0.005 for variances). The PORR varied from 21.89 percent (Dart) to 71.94 percent (Sidestream). The PORR of the Sidestream (71.94 percent) was significantly greater than all others (p<0.05). The PORR of the PARI-JET (52.49 percent) and the PARI LC JET (52.28 percent) had a greater percent of particles in the respirable range than all others except the AquaTower (p<0.05). Different units of the Aquatower were highly variable in this regard.

**Respiratory Particle Delivery Rate**

The RPDR is shown in Figure 4. There was a highly significant difference in the means and variances among the groups (p<0.0001 for means, p<0.005 for variances. The RPDR varied from 0.05 ml/min (Acorn-II) to 2.8 ml/min (AquaTower). The RPDR for the PARI-JET (0.26 ml/min) and PARI LC JET (0.24 ml/min) did not differ significantly from the AquaTower (0.29 ml/min) and the Sidestream (0.19 ml/min). However, the output among units of the Aquatower was highly variable. The RPDR for the Sidestream did not differ significantly from the Aquatower, PARI-JET, and PARI LC JET or from the DeVilbiss or Downdraft. The remaining models all were different at the p<0.05 level.

**Volume Mean Diameter**

The volume mean diameter (VMD) represents the midpoint in microns where 50 percent of the particles are smaller and 50 percent are larger than the VMD value and is comparable to the mass median aerodynamic diameter (MMAD). The VMD varied...
The reusable nebulizers, different JET (4.38 all of have compared represents study the variation ability which facilitates comparison of VMDs and differences number by four Squares about 3.

FIGURE 3. Percent of particle output in the respirable range (1.0 to 5.0 μm). Diamonds indicate 95 percent confidence intervals about the mean (horizontal line) based on pooled variances. Squares indicate the means of triplicate determinations with the four units of that model. Names, means, and SDs of the models by number are given in the table below the figure. Overall differences between the means and variances were significant at p<0.0001 and p<0.005, respectively.

from 3.77 μm (Sidestream) to 7.20 μm (Dart). The smallest VMDs were Sidestream (3.76 μm), PARI LC JET (4.38 μm), and PARI-JET (4.84 μm); each was significantly different from the others and from all the remaining models (p<0.05). The extreme variability of the Aquatower precluded meaningful comparison.

DISCUSSION

In this study, we have demonstrated a highly significant variation in the output characteristics of 17 different reusable nebulizers, commercially available in the United States and intended for delivery of aerosol medication to the lower respiratory tract. This study represents an extension of previous studies that have compared a smaller number of nebulizers, not all of which were available in the United States.6-14 We have confirmed the reported variability in rate and extent of nebulization as well as the percent of the aerosol output in the respirable range (<5 μm). We have also combined these variables into a single parameter: the rate of delivery of respirable particles, which facilitates comparison of nebulizer models.

This expression of nebulizer performance also varied markedly among the nebulizers studied.

Jet nebulizers are commonly used for the delivery of bronchodilators, antimicrobial agents, and for bronchial challenge studies. The desirable characteristics for a nebulizer may vary among these different indications.10,13 For treatment of acute bronchospasm or for economy of patient time, a high rate of delivery of bronchodilator medication is desirable.6 For delivery of an expensive medication, a nebulizer that delivers the greatest percent of medication from the nebulizer bowl may be most desirable, even if the delivery rate is not maximal. For diagnostic and research challenge studies, the greatest possible reproducibility between different units of a particular model may be most important. The results of this study suggest that some available nebulizers are not optimal for any of these indications.

In this study, we only examined the delivery of aerosol particles. We did not examine the delivery of drug. It has been shown that albuterol and other medications are delivered to a lesser degree than the diluent, particularly as nebulization continues.17 This
is presumably due to the increasing contribution of evaporation to the loss of diluent from the nebulizer bowl. While analysis for drug delivery might have varied somewhat from that of particles, the principles of evaporative loss of diluent have been shown to apply to nebulizers of various manufacturers. It is unlikely that this further analysis would have greatly altered the outcome of the study.

In summary, commercially available jet nebulizers, all with the same initial fill, and all driven by the same air compressor, varied greatly in the total delivery of fluid, the time required to deliver this fluid, and the percent of the delivered fluid in the respirable range. This resulted in a variability of total output of twofold, of the time required for nebulization of ninefold, and of drug delivery in the respiratory range per minute of eightfold. These performance characteristics as well as the reproducibility from unit to unit should be considered in selection of a jet nebulizer.

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