Humidification in Intensive Care: Are We There Yet?

It is now more than 60 years since the polio epidemic in Denmark in 1952 that led, at least partly, to the development of artificial ventilation.[1] In the report of that epidemic, Lassen stated that "A good humidifier is essential: otherwise incrustation of secretions may occur." Subsequent to the polio epidemic, a heated humidifier was described by Marshall and Spalding in 1953,[2] and Drägerwerk AG & Co filed a patent for a heat-and-moisture exchanger (HME) in 1954.[3] It is sobering to reflect now that even after 60 y, 2 topics, (1) what makes a good humidifier and (2) which of the 2 types of device, heated humidifier or HME, is better for the patient, are still being debated. To add to the debate, there is the more recent

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development of an active HME, where the performance of an HME is augmented by the addition of water, which is then heated and evaporated.[4] An additional topic that follows from topic (1) is how best to test these various devices to obtain appropriate information on humidification performance to make an informed decision.

In this edition of RESPIRATORY CARE, Lellouche et al[5] add to this debate by comparing the performances of 2 HMEs and an active HME at different ambient temperatures and minute ventilations ($\dot{V}_E$). The authors conclude that variations in ambient temperature and $\dot{V}_E$ have negligible effects on the humidification performance of HMEs and active HMEs. This is an important addition to the evidence available on the use of these devices. However, there are some important issues arising from this work.

International Standards

International standards are available for use when testing the performance of many different types of medical devices. The use of standards helps ensure that data obtained on the performance of devices by different groups can be usefully compared. This then helps users and purchasers make an informed choice when choosing between different devices.

The current international standard for HMEs (ISO 9360-1:2000) includes tests for the effect of $\dot{V}_E$ on humidification performance by specifying 4 different test conditions, but not the effect of ambient temperature.[6] The current international standard for heated humidifiers (ISO 8185: 2007) includes the effect of variations in continuous gas flow, but not $\dot{V}_E$ (in terms of tidal volume [V_T] and breathing frequency) or ambient temperature.[7] Because the test methods specified for HMEs and heated humidifiers are different, it is difficult to make a comparison between the humidification performances of these 2 types of devices.

Effect of $\dot{V}_E$ on Humidification Performance of HMEs

$\dot{V}_E$ is the product of V_T and frequency (f), such that $\dot{V}_E$ (L/min) = V_T (L) × f (breaths/min). Therefore, to alter $\dot{V}_E$, the V_T, frequency, or both can be varied.

Lellouche et al[5] chose 2 values of $\dot{V}_E$ (Table 1). They concluded that variation in $\dot{V}_E$ had negligible influence on the humidification performance of HMEs. This is impressive, as $\dot{V}_E$ was doubled from 10 to 20 L/min (Table 1). However, as $\dot{V}_E$ is composed of 2 components (as shown in the above equation), it is perhaps worth investigating this further. The increase in V_T was modest, an increase of 0.15 L from 0.50 to 0.65 L (30%). The increase in frequency from 20 to 30 breaths/min was greater (50%), but which of the 2 components of $\dot{V}_E$, V_T or frequency, is likely to have a greater effect on humidification performance?

Effects of V_T and Frequency on Humidification Performance

The first edition of the international standard for HMEs was published in 1992.[8] This included a test method for determining the humidification performance at different combinations of V_T and frequency (the inspiratory-expiratory ratio was also varied for some test conditions, but is not included in this discussion). For HMEs intended for

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DOI: 10.4187/respcare.03232

Table 1. Test Conditions Used by Lellouche et al[5]

Test Condition	Tidal Volume (L)	Frequency (breaths/min)	Minute Ventilation (L/min)
1	0.50	20	10
2	0.65	30	20

Table 2. Test Conditions for Heat-and-Moisture Exchangers Intended for Use With Adults From ISO 9360:1992[8] Used by Eckerbom and Lindholm[9] and Branson and Davis[10]

Test Condition	Tidal Volume (L)	Frequency (breaths/min)	Minute Ventilation (L/min)
1	1.0	20	20
2	1.0	10	10
3	0.5	20	10

use with adults, the test conditions comprised the V_T values and frequencies shown in Table 2.

Thus, comparing results from test conditions 1 and 2 indicates an effect of changing the frequency, whereas comparing results from test conditions 2 and 3 indicates an effect of changing the V_T, provided the effect of changing the frequency was small.

Two studies compared the humidification performance of HMEs using test methods and conditions based on the ISO 9360:1992 standard.[9,10] In both studies, there was a more marked effect on the humidification performance upon changing V_T from 0.5 to 1.0 L (equivalent to a 100% increase) compared with changing the frequency from 10 to 20/min (again, equivalent to a 100% increase), suggesting that V_T has the primary effect on humidification performance, whereas the frequency effect is secondary. The difference in humidification performance under the different test conditions was small for those devices that performed well, but the effect of increasing V_T to 1.0 L for some devices that performed more poorly at V_T 0.5 L was marked.

The more pronounced effect of V_T on humidification performance compared to frequency also makes sense from a theoretical point of view. An HME is designed to retain moisture during expiration and release the retained moisture during inspiration to humidify the inspired gas. The expired gas produced by the test rig used by Lellouche et al[5] was set at a temperature of 33°C with an absolute humidity level of 35 mg/L. Therefore, an expired V_T of 0.5 L would contain 17.5 mg of water vapor, and the HME would be designed to retain a large proportion of this water (eg, to return 30 mg/L would require an efficiency of 86%). Doubling the V_T would double the mass of water vapor (to 35 mg), and the capacity of the HME to retain this additional mass of water vapor may be limited, particularly for some devices. In contrast, the effect of increasing the frequency is only to reduce the time that the HME has available to retain the moisture; it does not affect its capacity to do so.

Table 3. Test Conditions for Heat-and-Moisture Exchangers From ISO 9360-1:2000[6]

Test Condition	Tidal Volume (L)	Frequency (breaths/min)	Minute Ventilation (L/min)
1	1.0	10	10
2	0.75	12	9
3	0.50	15	7.5
4	0.25	20	5

The current international standard for HMEs[6] still requires a test to be carried out using a test condition with V_T 1.0 L (Table 3). This is much greater than the V_T used as a maximum by Lellouche et al[5] (0.65 L). Hence, the effect of increasing V_T on performance may be missed if one instead concentrates on the effect of the composite term $\dot{V}_E$ on humidification performance.

Effect of Ventilation Strategy on Humidification Performance and Use of HMEs

Lellouche et al[5] used 2 V_T values in their study and concluded that $\dot{V}_E$ had negligible influence on humidification performance. This contrasted with the conclusions reached in the 2 studies by Martin et al in 1992[11] and 1995[12] cited by Lellouche et al, in which the adverse effect of increasing $\dot{V}_E$ above 10 L/min on humidification performance was first described. However, the mean ± SD V_T values used to ventilate the subjects in the 2 studies by Martin et al were 0.785 ± 0.132 L and 0.694 ± 0.143 L, respectively; both means are therefore above the greater of the 2 V_T values used by Lellouche et al[5] (0.65 L). The effect noted by Martin et al may have been missed by Lellouche et al not only because of the different devices used by the authors, but also because of the difference in V_T values.

It is also interesting to note that the mean $\dot{V}_E$ during the clinical study carried out by Lellouche et al[5] was 12.4 L/min. In the 2 studies by Martin et al[11,12] cited by Lellouche et al, the mean ± SD $\dot{V}_E$ values were 13.1 ± 1.7 L/min and 11.9 ± 1.2 L/min, respectively, similar to that in the clinical study by Lellouche et al. However, comparing these values and the $\dot{V}_E$ values specified in the current edition of ISO 9360-1:2000 (Table 3) to the $\dot{V}_E$ values of 10 and 20 L/min used in the bench study by Lellouche et al suggests that a test condition using $\dot{V}_E$ 20 L/min is rather excessive (although in keeping with the maximum $\dot{V}_E$ specified in the first edition of ISO 9360:1992 [Table 2][8] and from the studies already mentioned[9,10]).

Martin et al[11] also stated a mean ± SD for the ventilation strategy of 12.4 ± 3 mL/kg (range 8.1–16.4 mL/kg) in

the study from 1992. This is larger than would be considered appropriate today, more than 20 years later, when guidance has been published to start artificial ventilation at 8 mL/kg and to reduce ventilation to 6 mL/kg (or to a minimum of 4 mL/kg) when possible.[13]

The guidance on ventilation strategy is based on predicted body weight.[13] For example, for males, the predicted body weight (kg) is $50 + 2.3 \times$ (height [inches] $-$ 60). For a male who is 6 ft tall (72 in), the predicted body weight is $50 + 2.3 \times (72 - 60) = 77.6$ kg. Following the guidance for an 80-kg male, the V_T would range from 320 to 640 mL, which is considerably less than the maximum V_T of 1.0 L specified in the standard. However, manufacturers are obliged to declare a range of V_T values over which their HMEs can be used, and it is appropriate that the performance of the HME should be tested at the limits of that range.

In general, from the earlier discussion, in order to obtain the best humidification performance from an HME while maintaining the same $\dot{V}_E$, it is preferable to reduce the V_T and to increase the frequency where possible. Fortunately, this also is in line with the guidance to help protect the patient's lungs.[13]

Good humidification is one criterion to consider when choosing an HME. Other criteria are dead space (from the internal volume) and the work of breathing (from the resistance to gas flow).

Unfortunately, following the guidance to reduce the V_T causes the effect of the HME's internal volume on rebreathing to be more pronounced. Lellouche et al[5] included 2 HMEs in their study, the Hygrobac and the Hygrobac S (Tyco Healthcare, Raleigh, North Carolina), with 2 different internal volumes, 95 and 45 mL, respectively. Given the small difference in humidification performance between these 2 devices, the Hygrobac S, with its smaller internal volume, is probably the preferred option if V_T is being reduced. However, this advantage is slightly counterbalanced by the fact that its resistance to gas flow is ~10% greater (2.3 compared with 2.1 cm H_2O/L/min).

What Is a Good Humidifier?

Returning to the question of humidification performance: what level of humidification performance would constitute a good humidifier? On the basis of a recent review of the literature, I suggested that 30 mg/L, as originally proposed by Chamney in 1969,[14] be considered an appropriate minimum level of humidification.[15] Interestingly, this was the level set as the minimum level in the first edition of the international standard for heated humidifiers,[16] but this was subsequently increased to 33 mg/L[7] (the current standard for HMEs [ISO 9360-1:2000] does not specify a minimum level of performance[8]). However, this is above the level that can normally be delivered by HMEs (confirmed by Lellouche et al[5]). Given the level of use of HMEs over the past 20 years or more to provide humidification during long-term mechanical ventilation in ICUs for a broad range of patient groups and the number of studies that have been carried out attesting to their acceptability, this seems rather high as a minimum level. As Lellouche et al[5] pointed out, there is "no clinical demonstration of the superiority of delivering 40 versus 30 mg H_2O/L," and this is also true for 33 versus 30 mg/L. The optimum level of humidification may, of course, be $>$ 30 mg/L.

Effect of Expired Temperature and Humidity on Humidification Performance

Lellouche et al[5] set the temperature and absolute humidity of the air expired from their test rig at 33°C and 35 mg/L, respectively. As stated above, to return 30 mg/L under these test conditions would require the HME to be 86% efficient in retaining and releasing water vapor. The test condition for the expired gas specified in the first edition of the international standard for HMEs[8] was an expired air temperature of 34°C fully saturated with water vapor, equivalent to a moisture content of 37.6 mg/L. To return 30 mg/L under these test conditions is then less of a challenge for the HME, as the required efficiency is now only 80%. In contrast, if the HME is still 86% efficient, then it would return 32 mg/L. The current edition of the standard only specifies the temperature of the water bath in the test rig (37°C); the expired temperature is allowed to vary depending on the performance of the HME. However, if there was no cooling from the water bath to the mouth of the test rig, then expired air would contain 44 mg/L at 37°C, with obvious consequences for determining the humidification performance of HMEs (however, it should be noted that the current edition of the standard determines humidification performance in terms of net moisture loss from the test rig and not moisture returned to the patient, thus making comparisons between different sets of data even more difficult). In contrast, early work in this area, for example that of Branson[17] (carried out prior to publication of the first edition of the standard for HMEs), used an expired temperature of 32°C. Fully saturated air at this temperature has an absolute humidity level of 34 mg/L. Hence, there is less humidity available for the HME to return. Clearly, it is important that if comparisons are to be made, the same test protocol (including temperature and humidity) should be used.

Effect of Ambient Temperature on Humidification Performance

The negligible effect of ambient temperature on humidification performance of HMEs found by Lellouche et al[5] is welcome news for those working in areas of the world

where the ambient temperature is not maintained close to the ambient temperatures specified in the standard (23 ± 2°C) when carrying out tests, and this indicates that HMEs can still be used to provide adequate humidification in these different climates. As changes in ambient temperature have only a negligible effect on the humidification performance of HMEs, it is probably immaterial that such a test is not included in the international standard for HMEs. However, previous work by the authors[18] demonstrating an effect of changes in ambient temperature on the performance of heated humidifiers suggests that a test to determine this effect should be developed for the international standard.

Conclusions

The availability of independent evidence of the performance of HMEs is crucial to allow an informed choice to be made between the many different models available on the market, and Lellouche et al[5] and others working in this area are to be congratulated for providing relevant data.

However, care should be exercised when stating and using different test conditions for determining the humidification performance of HMEs: V_T and frequency have independent effects on humidification performance that can be hidden if only the $\dot{V}_E$ is stated.

The test methods specified in the current international standards to determine the humidification performance of HMEs and heated humidifiers are different and do not make comparisons between the different types of devices easy to make. It is hoped that a general test method can be developed that can be used for both types of devices (and for testing active HMEs) to make comparisons of performance easier. Consistent expired temperature and humidity settings are clearly important.

However, what is really needed now is a definitive study to determine the minimum (or preferably the optimum) level of humidification required for long-term artificial ventilation. Hopefully, we will not have to wait another 60 years.

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