A PROPOSED METHOD FOR QUANTIFYING LOW-AIR-LOSS MATTRESS PERFORMANCE BY MOISTURE TRANSPORT

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Because they are believed to control the microclimate of the skin by removing or reducing perspiration accumulation and providing localized cooling, low-air-loss mattress systems are used for the treatment and prevention of pressure ulcers. However, no clear, universally agreed upon definition exists for their design, and reproducible standards on which to base their performance or assess their anticipated clinical effect are lacking. A clinically relevant, reproducible, mechanistic, controlled laboratory test methodology was developed to assess and compare the moisture transport properties of a variety of low-air-loss products by measuring and balancing the complete moisture transport into and out of low-air-loss mattress systems. Using a controlled and defined operating environment, the low-air-loss system is moisture- and weight-loaded using a patient skin moisture analog. Moisture and air transport properties into and out of the environment are measured. Total moisture balance, comparing total moisture change of the analog against the time-based moisture transport data, validates the results. Using mattresses from various manufacturers, time-based data using the study method showed important differences in low-air-loss characteristics related to mattress system design, performance, and function. The observed time-averaged moisture transport performance values indicate that several systems meet an acceptable minimum level of performance, but performance levels between different low-air-loss mattress systems vary markedly.

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Low-air-loss (LAL) mattress systems have been used for the treatment and prevention of pressure ulcers for many years. Pressure ulcer development is related, in part, to the accumulation of heat and perspiration on the skin. Heat and moisture increase skin susceptibility to the damaging effects of pressure and shear and decrease the resiliency of the epidermis to external forces. Ongoing compressive forces on skin tissues are known to promote ischemia with subsequent development of pressure ulcers. Therefore, controlling the microclimate of the skin and providing a quality patient support system appear to be necessary to prevent pressure ulcers. Low-air-loss mattresses were developed and are used in the belief that they help to control the microclimate of the skin.1,3

Literature Review

Clinical studies. Results of LAL effectiveness studies have been mixed. Ferrell reported that, compared with a 10-cm thick egg-crate foam mattress, pressure ulcer healing rate improved when patients were placed on an LAL surface. In addition, Ferrell et al concluded that LAL is cost-effective for patients with “good healing characteristics and ‘mild’ ulcers.” Inman et al reported a significant decrease in the nosocomial pressure ulcer incidence rate for patients on LAL compared to standard hospital surfaces but found no differences in resolution of existing ulcers. Yarbrough et al, Holzapfel, and Charles et al reported clinical benefits of LAL. However, Hardin et al, Jesurum et al, and Warner reported no statistically significant difference with the
use of LAL and other standard support surfaces. Maklebust and Callum et al. point to the lack of well-designed, scientifically rigorous studies available in the literature and to an inability to draw conclusions from previous studies on the subject.

**Low-air-loss systems.** Low-air-loss was first described in medical literature in 1971 by Scales et al. They discussed a system of interconnected air chambers with a flexible, vapor-permeable film between the skin and the support air. The goal of this bed was to minimize the volume of air and the size of the inflation air pump compared to high-air-loss surfaces; thereby, achieving uniform load distribution to accommodate body forms, evaporate water from the support area, and control temperature and humidity. Since that first description, the number of available products called LAL has multiplied rapidly. Currently, dozens of products are on the market, featuring nearly as many construction methods. Because no definition of LAL has been put forth by an independent body that has met with the acceptance of the medical and manufacturing communities, clinicians have been left with assumptions of LAL mattress design and performance. Despite the prevalence of these mattress systems, no clear, universally agreed upon definition exists for their design — nor any viable, reproducible standards on which to base their performance or to assess their anticipated effect in clinical settings.

Intended specifically to remove or reduce perspiration accumulation and provide localized cooling of the skin to control the skin microclimate, LAL systems are used in conjunction with patient support systems to distribute torso loads. Mechanisms for achieving perspiration removal may consist of: 1) diffusive evaporation — drawing moisture by evaporation through and under the coverlet and away from the patient to cool the skin (latent phase change cooling), and/or 2) convective evaporation — moving air directly against the skin to evaporate and displace the moisture to cool the skin. Either mechanism depends on the system not only drawing moisture away from the patient, but also removing that moisture from the mattress system itself. If this is not accomplished, the patient lies in a damp environment susceptible to bacterial growth.

Low-air-loss broadly refers to a system comprising a mattress casing, a vapor permeable coverlet with or without lofting or cushioning material, and an air delivery system to move air under the coverlet and, in some cases, to leak through the coverlet. Some systems function as integral parts of patient support systems; whereas, others are not actively coupled. The term low-air-loss dates back to the original concept that included perforations in the air mattress support casing to allow air to leak out and through the coverlet. This increased the immersion of the patient into the mattress to disperse interface pressures. The idea was that the escaping air would help decrease the accumulation of perspiration on the skin and lower local skin temperature (by convective evaporation) to help in the prevention and/or treatment of pressure ulcers.

Alternative designs attempt to encourage moisture transport into the mattress system, both directly from the patient’s skin and the surrounding skin microclimate and by vapor diffusion (diffusive evaporation) and transport it away without the need to physically blow air on the patient to keep the skin dry and cool. Some designs use hybrids of these two mechanisms.

**Measuring product performance.** Objective criteria for comparing product effectiveness, as well as controlled scientific evidence of the therapy’s relative value in clinical intervention, are necessary. Many methods have been devised to measure the physiological effects of support surfaces, including cutaneous pressure mapping devices to measure interface pressures and thermography and Doppler to ascertain microcirculatory blood flow. However, to date, the only fairly objective and quantifiable method of comparing mattresses or possibly predetermining mattress effectiveness has been interface pressures. Skin-resting interface pressures, however, do not reflect bone-tissue interface or capillary closure pressures and cannot be used as the sole reason for clinical acceptance of any support surface.

**KEY POINTS**

- Low-air-loss (LAL) mattress systems have been widely used for many years, but no universally accepted definition for such systems exists and information about their performance and (relative) effectiveness is sparse.
- The method to assess and compare LAL systems described by the author may prove to be an important step toward providing clinicians with the comparative information they desperately need to make informed product decisions.
Nicholson et al proposed a performance test to measure the moisture vapor and heat transport capability of various mattress support systems that included LAL systems. The test, which draws from fabric tests in the textile industry, develops a microenvironment of controlled humidity and temperature above a sample of fabric of the LAL cover to simulate the steady state of diffusion of moisture through the fabric at physiological conditions. The moisture transport capability of the mattress system is inferred by measuring moisture transport from the controlled environment into the mattress cover. However, patient body weight load on the mattress is not included in this method—a significant omission because patient weight compresses the mattress materials and alters performance. Hence, the results are indicative of mattress cover vapor transmissibility, not a simulation of mattress performance in-situ. Reger et al report on a test to infer mattress performance that uses a water-saturated patient analog to provide moisture and energy to an LAL mattress system. The analog rests on the mattress surface and the mattress system is operated normally. The mattress performance is inferred from measurements of the temperature drop underneath the analog, reflecting latent energy removal for 90 minutes or less. The study lacks an analysis of the errors involved in such difficult-to-interpret measurements but offers qualitative results for moisture transport capability.

A reliable performance test should be able to quantify moisture transport into, through, and out of the mattress system, not just through the cover or into the mattress materials. Tests that quantify only average moisture or qualify latent energy into an LAL can provide misleading results and are subject to misinterpretation, especially when such tests are of short duration. A test must address a mattress system's tendency to retain moisture when attempting to transport it away from the patient. Further, a moisture transport time history can provide insight into the mechanism of mattress performance that time-averaged tests alone cannot offer.

Can mattress moisture transport be measured in a way that provides useful information related to mattress performance effectiveness? What information does such knowledge provide? What role does the rate of airflow play in terms of mattress effectiveness and design efficiency? The test method proposed herein is intended to pilot a reliable, reproducible, and mechanistic tool to evaluate and compare mattress system performance and design effects based on moisture vapor (perspiration) transport. The proposed method quantifies the moisture transport into, through, and out of the complete mattress system using a patient analog and provides an interpretation of time-based moisture transport information in the context of mattress performance.

**Methodology**

**Transport conservation principles.** The laboratory test method design is based on transport conservation principles. This approach requires defining a controlled environment around the tested system and is known as a *control volume* in which inflow and outflow properties are noted by measurement. Transport properties such as temperature, airflow rate, and absolute humidity levels are measured into and out of the control volume with respect to time. The concept is that differences in the inflow and outflow transport properties reflect causal effects within the control volume. In this case, as perspiration is removed from the patient microclimate, it either must be transported out of the mattress system or retained within the system. Any moisture transported out of the system will be measurable in the transport properties out of the control volume. This is used to assess mattress system performance through its ability to move moisture away from a patient and away from the immediate mattress system environment. Moisture transported between two locations within the control volume must be retained within it, such as within the mattress coverlet or lofting materials beneath the patient.

**Configuration for testing.** In this method, a mattress system is operated in its normal configuration but within the control volume. All transport properties both into and out of this controlled space are measured. The patient's weight, heat, and perspiration loads are simulated by applying weight, energy, and moisture at the mattress cover surface. An accurate assessment of moisture transport through the mattress system is possible because the transport values (temperature, airflow, and humidity) are measured.

The system design allows for different mattresses to be tested in an identical manner (see Figure 1). The control volume is defined by placing the mattress with-
in a sealed vinyl mattress environmental chamber (MEC) to create a controlled environment. The MEC is oversized to accommodate different mattress system designs and airflow rates. The MEC contains a length-wise, zippered opening to allow mattress placement. This opening is sealed with tape at the start of all tests.

**Airpath.** Airflow is controlled and measured as it enters and leaves the MEC. Inlet air for the mattress system is provided, using the manufacturer connections, from the mattress’ control unit via pass-through ports that are welded into the MEC and sealed to prevent outside infiltration of air or humidity. The air is taken directly from the laboratory room. Mattress outflow exits the MEC through eight, equally spaced, 12-mm peripheral outlets, which also are sealed pass-through ports with connectors. Each outlet is connected in parallel to a single 37-mm diameter plastic pipe that runs the circumference of the MEC and also serves as the system air exhaust manifold and flow exit. This design was created by trial and error but the final design was selected because it: 1) prevents pressure build-up within the MEC that might affect air flow rates and 2) provides a convenient single exhaust port for measuring exit transport properties. For the reported tests, the space outside of the MEC was a normal laboratory environment maintained as HVAC-conditioned space (nominally: 23°C ± 1.5°C and 42% ± 4% relative humidity).

**Perspiration simulation.** A typical inactive patient with a body temperature of 37°C perspires about 600 g/day in a continuous manner.

![Figure 1](image-url)  
**Figure 1**  
The control volume and test concept of the mattress environment chamber and patient simulation.

An average prostrate patient provides a mattress pressure loading of approximately 10 mm Hg over the torso area. To simulate patient perspiration, weight load, and body temperature in a reproducible manner, the method used here consists of a moisture-bearing patient moisture reservoir (PMR). The PMR mimics the average-sized torso, is temperature regulated, and weighted to provide proper mattress loading at the mattress-patient interface.

The reservoir or PMR rests on the mattress and is contained within the MEC. The PMR consists of a 0.28-m² (0.46 m x 0.6 m) polypropylene, staple fiber, non-woven fabric towel that is moistened to a nominal total wet mass of 195 g (44 g dry). This total wet mass was consistent to within 5 g for each test as measured on a lab scale (Mettler BD202, Mettler-Toledo, Inc., Columbus, Ohio; accuracy: within 0.02 g). Patient moisture reservoir mass was measured before and after each test. The PMR is placed on the top and centered on the mattress. A pattern marked on the mattress allows the PMR to be resituated in a reproducible manner for repeated tests.

**Temperature.** A water bladder is used to provide temperature regulation for the PMR throughout the execution of each test. The water bladder rests on the PMR but is placed outside the vinyl boundary of the MEC; thus, outside the control volume. The water bladder is 0.42 m² (0.46 m x 0.91 m) and completely overlays the PMR. A pattern is marked on the MEC at the start of each series of tests to conveniently allow the bladder to be resituated in a reproducible manner. For temperature control, a water bath circulator (Cole-Palmer Polystat 12110, Cole-Palmer, Vernon Heights, Ill.) provides a steady circulation of water of 12 L/min through the bladder maintained at 36.9°C ± 0.1°C. The 4-L water bladder is constructed of heavy vinyl and consists of two joined chambers that are interconnected only near the bladder’s base. The inflow port is
attached at the top of one chamber and the outflow port at the top of the other chamber. This design allows a directionally continuous circulation of water through the bladder.

Patient load is simulated by the total distribution of weight over the top of the PMR. A thick, dense (7.5 cm, 64 kg/m³) foam pad of 0.42 m² (0.46 m x 0.91 m) is placed over the water bladder and weighted down with iron plates of known mass and distributed over the upper surface. The distributed load on the PMR is based on the weight of the water bladder, foam pad, and plates over the contact area of the water bladder.

The PMR approach provides a batch method for simulating patient perspiration — that is, the PMR continues to lose mass as moisture is drawn from the reservoir through the mattress system and will lose mass at a rate that depends on the LAL system tested. The PMR proved capable of simulating several hours of typical perspiration load, so a mattress system should be able to achieve a steady rate of moisture transport for a reasonable portion of a test. This approach is reproducible and provides a standardized method of handling the patient simulation.

Securing measurements. Transport properties are measured both into and out of the control volume throughout the test. Airflow rate and inlet air temperature are measured using an inline thermal mass flow meter (TSI Model 4140, TSI, Inc., St. Paul, Minn.; flow accuracy: within 2% of reading, temperature: within 1˚C). Air moisture is determined by measuring absolute humidity. The humidity probe used incorporates a high sensitivity, immersion-type capacitance sensor placed within the air stream and operated with a matched indicator probe (Vaisala HMI41/HMP46, Vaisala Group, Woburn, Mass.). Accuracy in moisture measurement with good time response is important in these tests. The selected measuring system measured airborne moisture to within ±0.15 g H₂O/kg dry airflow in these tests, with a response time of seconds.

Airflow rate and temperature into the mattress were measured inline at the connections between the manufacturer’s mattress control box and the mattress system. The humidity of the air drawn into the control box was measured at the control box intake. The humidity and temperature of the flow out of the control volume was measured at the exit of the exhaust manifold. In this way, the total moisture transport from the patient moisture reservoir and out of the mattress system could be measured with respect to time.

Spatially distributed temperature measurements were taken under the water bladder using six, disc-style thermocouple sensors connected to a readout device to monitor the uniformity of temperature regulation over the PMR. Temperatures were always noted to be within 0.1˚C of the set point. In addition, an extra sensor recorded room temperature. No extra attempt was made to insulate the external surfaces of the MEC from heat loss.

During the test, the mattress system was operated within the MEC for 12 hours without moisture loading so the system could achieve a steady, room-conditioned state. Logged measurements were studied to ensure that this unloaded steady state had been achieved before testing. To initiate moisture tests, the PMR was moistened, weighed, and placed on the mattress. The mattress was sealed, the water bladder and loading were applied, and the mattress control panel turned on. For reported test results, measurements were taken every 10 minutes and continued until the unloaded steady operating conditions were again achieved, at least 8 hours depending on mattress. The system then was disconnected and the weight of patient moisture reservoir measured. The difference in the wet-to-dry mass of the PMR provided a concomitant check of moisture removed by the system and was compared to the integrated value of moisture removed as measured by the humidity probe. If these data agreed to within the uncertainty of the test, they were considered valid. The proposed method shows the complete test uncertainty in reported steady state moisture transport to be under 7% (stated at 95% confidence intervals) for all tests. This is less than other methods considered, including latent heat measurements at the PMR-mattress interface. More importantly, the method directly measures time-based moisture transport.

Tests were conducted on LAL mattress systems from different manufacturers to demonstrate the viability of the proposed methodology and to compare moisture transport mechanisms (see Table 1). Four mattress systems, labeled A through D, were available for all tests; they form the basis of the validation. In addition, two other mattress systems, labeled E and F, were available for only a single test each. Each mattress uses a somewhat different design to remove and transport moisture
from a patient. Regardless, the test method measures the total time-based moisture transport under a simulated patient load.

**Results/Discussion**

Tests were repeated three separate times on different days for the four LAL mattress systems, A through D. The data reported are from these repetitions. Each mattress system was found to have its own moisture transport time-history signature characteristic of the mattress system design and function (see Figure 2).

Moisture transport has been normalized by mattress airflow rate, which differs for each mattress, to represent comparable moisture transport efficiencies.

The time history (see Figure 2) reveals three characteristic zones found with each mattress: ramp-up, quasi-steady, and dry-out (indicated by example using Mattress A). Specifically, the ramp-up zone reflects the start-up portion of the test when the PMR is full and recently applied to the mattress. Moisture levels rise rapidly. The quasi-steady zone reflects the portion of the test when moisture transport through the LAL system is relatively steady. These moisture rates are relevant to differences between mattresses and are used for reporting “steady” LAL mattress performance. The dry-out zone reflects the emptying condition of the PMR. The moisture removed in this zone is the trace moisture from the PMR and moisture retained within the mattress environment.

The quasi-steady zone is the portion of the test that may best reflect mattress performance during continued patient use because it models a patient’s ongoing perspiration rate. Here, the moisture transport out of the system is balanced against the ability of the mattress system to move moisture away from the PMR. Vapor transport through the cover limits performance in this zone. All mattress systems tested exhibited a quasi-steady zone in their time history of at least 100 minutes; values measured over this duration were used to average the steady performance values measured.

Within the dry-out zone, a mattress system designed to transport the moisture directly from the patient environment to the mat-

**TABLE 1**

<table>
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<th>Test Product Construction Comparisons</th>
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<tr>
<td><strong>Coverlet top fabric</strong></td>
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<td><strong>Coverlet lofting material</strong></td>
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<td><strong>Air delivery to coverlet</strong></td>
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**Figure 2**

Representative moisture transport time history for mattress systems used to demonstrate the proposed test methodology concept.

da = dry air
tress system exit will show a sharp drop-off to zero in moisture transport. On the other hand, a system design that tends to redistribute or retain moisture in the bedding, covering, or mattress region, or one that does not move moisture readily, will show a more gradual drop-off in the dry-out zone.

Mattresses A and C show a sharp drop-off from the quasi-steady through the dry-out zones (see Figure 2). With these two mattresses, any traces of visible moisture within the MEC dissipated quickly, consistent with the noted data trend. Mattress B shows a more gradual drop-off from peak performance to full dry-out than mattresses A or C. Visible moisture was still apparent in regions of this mattress for times well into the dry-out zone. The distinction between the quasi-steady and dry-out zones is even less clear with Mattress D, whose time-history tends to follow a tapered drop from maximum performance. Visible moisture was apparent for some time after the maximum performance had diminished.

From these data, it is clear that the proposed test methodology is effective at quantifying the moisture transport time-based behavior, as well as differences among the mattress systems. The proposed performance test documents the mechanism of moisture transport from a patient to the room environment by mattress system with relevance to the clinical setting.

The moisture transport effectiveness of each mattress was determined as follows: An average of the time-based maximum performance for the same four LAL mattress systems was computed by using the moisture transport rates measured during operation in the quasi-steady zone. The quasi-steady zone provides the maximum continuous moisture transport values measured; hence, it reflects a maximum steady performance and one most relevant to the clinical setting. The reported values are based on the pooled average from three repeated tests of the moisture transport rates, which are the time average measured over a 100-minute period during operation in the quasi-steady zone. Data were normalized by the PMR area to achieve the relative moisture transport effectiveness results (see Figure 3). These quantitative results differ markedly for the four mattress systems. A factor of 2.17:1 is evident between the highest performance value and the lowest. Interestingly, the mattresses’ moisture transport effectiveness was inversely related to the magnitude of their airflow rate. In general, a more efficient design should achieve a level of acceptable performance at moisture transport at a lower airflow rate.

A typical patient perspiring at about 600 g/day over the average 1.8m² body surface area yields a 13.9 g/hr-m² - moisture rate, a value that can be taken as a minimum for the needed performance for any mattress system to transport moisture away from a patient as it is produced. However, as the data in Figure 3 were normalized using the 0.28-m² area of the patient moisture reservoir, that value should be adjusted and taken at 89 g/hr-m². In clinical trials, Flam et al reported peak skin moisture measurements of 30 g/hr-m² for patients on a standard hospital mattress, which provides a reasonable baseline for comparing LAL systems with conventional systems. Therefore, these two performance values provide some limits for desirable performance for LAL mattress systems. All four of these mattresses met this 30 g/hr-m² standard mattress performance constraint. Mattress A and Mattress C are closest to meeting the higher performance value within the test uncertainty. In clinical situations where required, the results indicate that all four mattresses tested should provide some improvement over a standard hospital mattress at transporting moisture away from a patient’s body but that the level of performance varies markedly. Further, these performance results do not attempt to address any negative aspects to decreasing humidity in the skin micro-environment.

Test-averaged mattress performance was determined by totaling the moisture transport for the entire duration of a test divided by the time required to transport...
that moisture (see Figure 4). In addition to the four mattresses tested above, two additional mattresses were available (Mattresses E and F) and tests were conducted on each for one test run. The relative performance of each of the mattresses reported above remained the same, although the test-averaged performance values are lower than the maximum performance values, as can be expected.

Mattresses E and F show greatly reduced test-averaged performance compared to their peers, possibly attributed to two causes. First, each uses a substantially lower airflow rate. As the previous results show, a higher flow rate does not directly correspond to better performance; rather, a given design will have a minimum airflow requirement to meet minimum effective performance. Secondly, their particular construction allows for many of the mattress perforations for air bleed to be blocked off under the weight load of the patient, preventing air to flow under the patient (or the patient analog in these tests). Thus, simulation of patient weight load is important in tests reporting mattress performance.

Conclusion
A reproducible controlled test methodology has been developed to measure and balance the complete moisture transport into, through, and out of LAL mattress systems. The test was constructed to measure the time-based moisture transport mechanism of LAL mattress systems that are purported to offer benefits in patient comfort and therapy through a reduction in moisture and heat within the patient-bed environment. The developed methodology is relatively simple but well controlled. It offers a standard by which to test and report the performance of different designs of LAL mattress systems. The results are applicable to the clinical setting in testing a mattress’ ability to transport moisture from a patient’s body surface; thereby, decreasing maceration.

The observed differences in time-history test behavior of the LAL mattress systems tested was directly related to their respective designs. All mattresses tested provided some degree of effectiveness at transporting moisture away from a patient and out of the mattress system. However, the level of effectiveness varied by more than 2 to 1. For the four mattress systems whose maximum steady performance values were measured, results suggest that these should show improvement in moisture transport over standard hospital mattresses. Results show that the moisture transport performance of a mattress system depends on the efficiency of its overall design and not on the magnitude of its airflow rate. Further research to develop study methods and compare support surface performance is warranted.

References
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