ASTM INTERNATIONAL

Journal of Testing
and Evaluation

Michael D. Leshner[1]

DOI: 10.1520/JTE20240404

Measuring Work of Breathing in an Infant Model: Comparison of Static and Dynamic Test Methods

Journal of Testing and Evaluation

doi:10.1520/JTE20240404 available online at go.astm.org/pubs

TECHNICAL NOTE

Michael D. Leshner[1]

Measuring Work of Breathing in an Infant Model: Comparison of Static and Dynamic Test Methods

Reference

M. D. Leshner, “Measuring Work of Breathing in an Infant Model: Comparison of Static and Dynamic Test Methods,” *Journal of Testing and Evaluation* https://doi.org/10.1520/JTE20240404

Manuscript received June 18, 2024; accepted for publication September 24, 2024; published online December 16, 2024.

[1] Leshner & Associates, PO Box 949, Elkton, MD 21922, USA (Corresponding author), e-mail: mleshner@expertlabs.com, https://orcid.org/0000-0002-2065-0137

ABSTRACT

When an infant’s face becomes engaged with soft bedding materials, a suffocation hazard may be present that is associated with increased work of breathing (WOB). When resistive materials impede airflow, an infant must work harder to breathe and maintain homeostasis. Airway stressors within the infant sleep environment are felt to be risk factors for sudden unexpected infant death (SUID). To quantify the WOB, experiments were performed using a mechanical breathing model for dynamic measurements and compared with a static test method. The model was configured to measure the dynamic pressure and volume of the lungs as they changed during the breathing cycle. Pressure and volume data were used to calculate the WOB per cycle for a range of 12 restrictive bedding materials and 3 types of foam. In addition, static airflow resistance measurements were made using the same materials. It was found that there is a useful correlation between static airflow measurements and dynamic measurements of WOB. The measurement methods and apparatus are described herein.

Keywords

suffocation, work of breathing, sudden infant death syndrome, sudden unexpected infant death, crib death, infant sleep environment

Plain Language Summary

When an infant’s face engages with bedding, airflow to and from the infant can potentially be restricted. When that happens, the infant has to work harder to breathe. This research models suffocation due to airflow resistance to calculate the work of breathing (WOB). These calculated results are compared with a simpler measurement of the minimum pressure during the inhalation portion of the breathing cycle. When the calculated WOB is compared with a static airflow test, the correlation is good. In other words, a static airflow resistance test is a reasonable indication of relative changes in WOB.

WOB

WOB is the amount of energy per unit time needed by the respiratory muscles to produce enough ventilation and respiration to meet the metabolic demands of the body. WOB is the product of pressure and volume integrated over each breath. During the inhalation portion of the breathing cycle, work is done by muscles to expand the lungs. When the muscles relax, the lungs passively deflate. If there is external resistance to airflow, the muscles need to work harder to inflate and sometimes to deflate the lungs. In the case of partial airflow resistance, prolonged exposure can exhaust and overcome an infant. In the case of extreme airflow resistance, an infant may not be able to work hard enough to overcome the resistance, with fatal consequences.[1]

To measure the WOB, the mechanical breathing model is adapted to measure the pressure and volume in the lungs as they change through the breathing cycle. Pressure and volume data are used to calculate the area on the negative side of the pressure–volume diagram, which is a measure of the WOB in the model and a proxy for the total WOB in an infant.

Mechanical Breathing Model

The breathing model used in this study makes use of twin elastic bellows having a compliance of 0.7 ml/mbar, similar to infant lungs.[2] A laser distance sensor (Micro-Epsilon opto-NCDT) monitors the free end of one lung to monitor its position, which indicates changes in lung volume, as shown in **figure 1**. The lungs are actuated by an external vacuum pump and control valves to intermittently supply suction in the space surrounding the lungs or vent to the atmosphere. The lungs reciprocate between volumes of 30 ml and 65 ml for a tidal volume of 35 ml. With a breathing rate of 44 breaths per minute, the model simulates a sleeping infant. Selection of lung volumes and breathing rate are consistent with the study performed by Carleton, Donoghue, and Porter[3] and used in the author's previous studies.[4,5] **Figure 2** illustrates the probe, representing the midface of an infant.

Experimental Apparatus and Methodology

Static and dynamic measurements were made using the same probe, made from a 76 mm diameter hemisphere. Two breathing holes 3 mm in diameter are spaced 12 mm apart. A "nose" is inserted between the holes, made

FIG. 1 Infant model lungs.

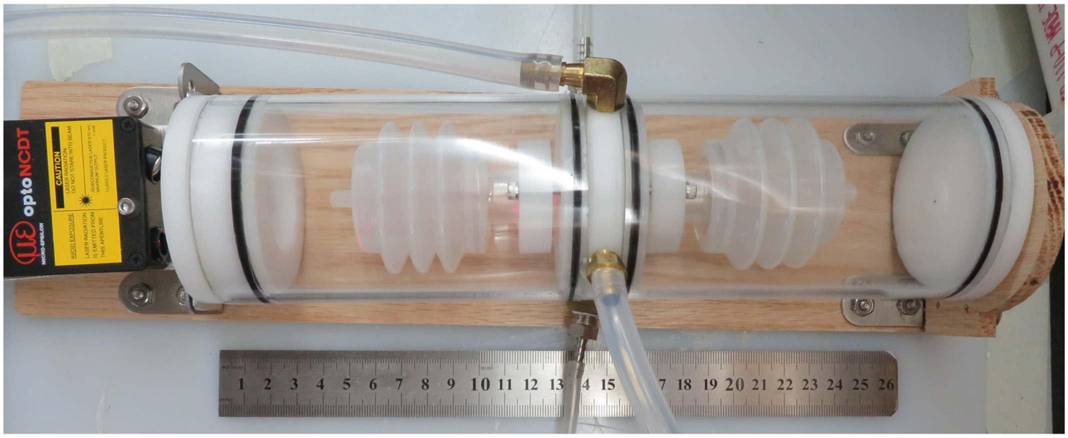
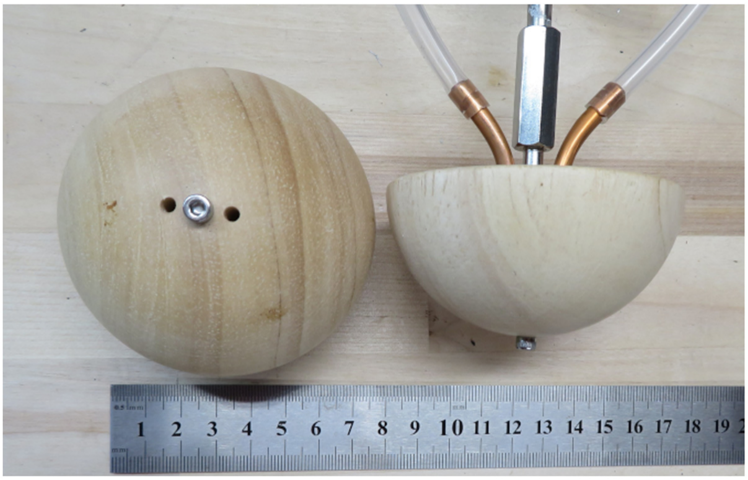


FIG. 2

Infant breathing probe.



from a 6-32 socket head cap screw, as shown in figure 2. In the dynamic measurements, the model breathes in and out through the probe. For static measurements, a fixed flow rate of 2 LPM is drawn through the probe.

Twelve bedding items were evaluated using three test methods:

- Static airflow resistance
- Dynamic measurements of pressure and volume
- Dynamic measurements of CO_2 rebreathing

A pair of soft lungs was employed to simulate the motion of an infant's lungs in response to pressure differences and allow measurement of the volume as it changes. The motion of the lungs was programmed to move a fixed volume of air, unlike a live infant who adjusts their respiratory rate and tidal volume to control CO_2 and O_2. Whereas an infant may hyperinflate in the face of increasing airflow resistance and dynamic lung and airway factors, the breathing model has a fixed tidal volume. For pressure and volume data, ten cycles were recorded and work was calculated for a representative cycle. Static airflow resistance measurements were made for comparison using the same probe, which is discussed subsequently. Measurements were repeated three times and the average is reported.

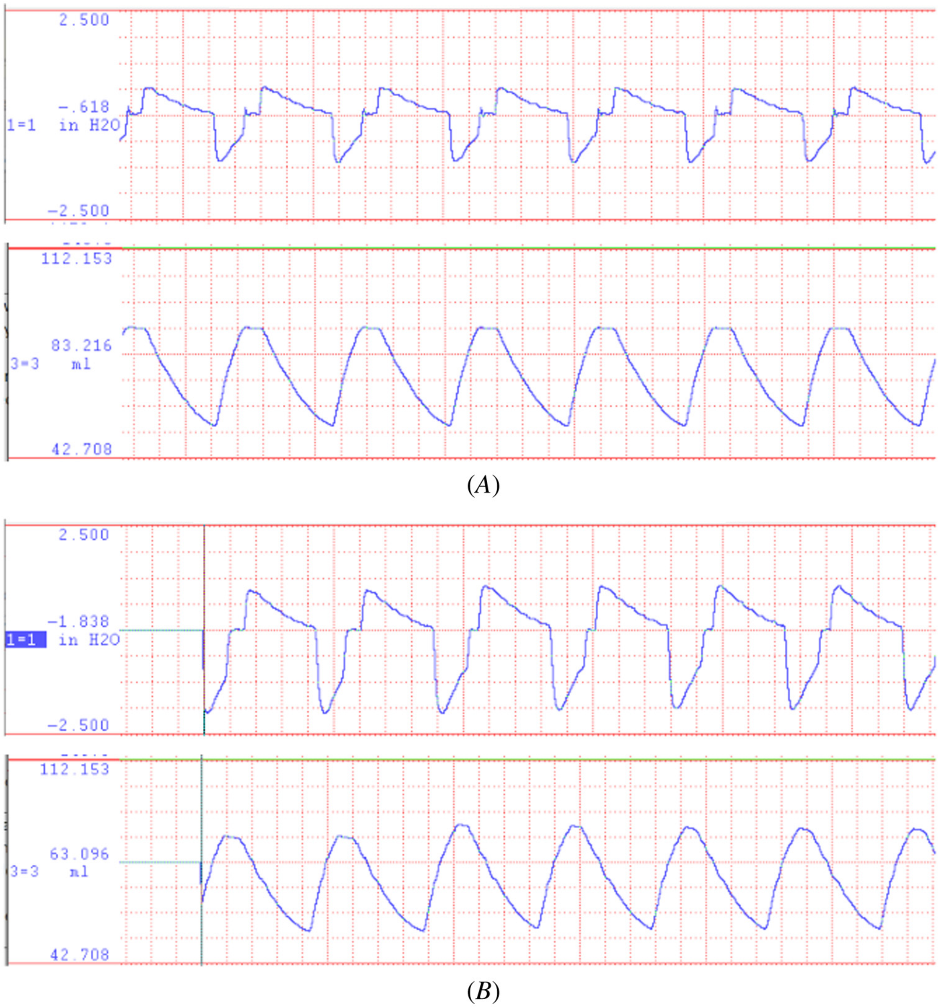
Pressure and Volume Measurement

Pressure in the breathing circuit was measured using a fast-response, low-range pressure transducer (Validyne P17). The laser distance measurement was calibrated against total lung volume. Pressure and volume data were recorded using a DATAQ DI-245 for signal acquisition and WINDAQ software for display and recording. Two examples of pressure and volume records are shown in figure 3 and represent the extremes in airflow resistance. Figure 3*A* shows the pressure and volume data for breathing through an open probe, elevated above the test surface. The probe itself causes some airflow resistance and figure 3*B* shows the pressure and volume data for breathing through the probe on a sheepskin surface.

WOB Calculation

To determine the WOB, the area within the pressure/volume diagram was calculated using the shoelace formula.[6] The area on the negative pressure side of the diagram represents work performed by the infant. Work per cycle is

FIG. 3 (*A*) Pressure and (*B*) volume waveforms.



multiplied by the breathing rate to calculate total work per unit time. An example of the pressure diagram is shown in figure 4. Figure 5 illustrates the shaded area of the P-V diagram, representing work.

Comparing all 13 bedding configurations, figure 6 shows the calculated measurements of WOB with values in excess of the baseline probe work. Importantly, the probe itself has a baseline level of resistive work.

Observation of Pressure Waveforms

For each of the 13 configurations, the pressure waveform was examined to pick off the minimum pressure. The relationship between the minimum pressure and calculated work is shown in figure 7. This relationship is convenient because it makes calculations unnecessary for determining whether a design change will increase or decrease the WOB. Observation of the pressure waveform is sufficient to assess changes in WOB.

FIG. 4

Lung pressure waveform.

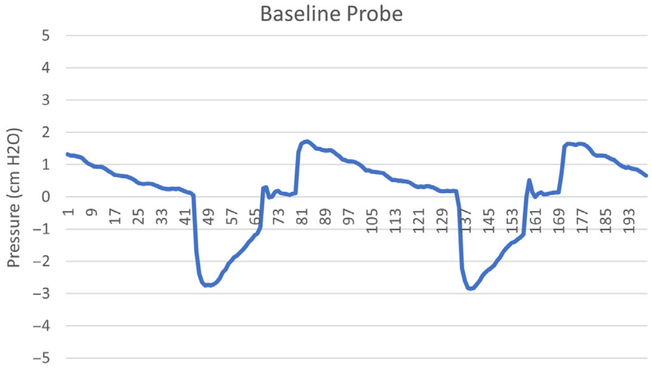


FIG. 5

P-V diagram.

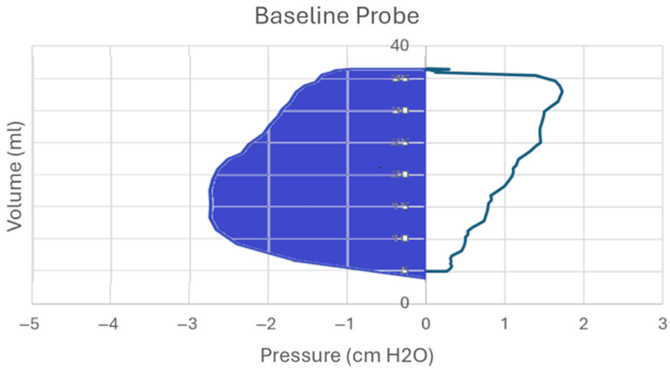


FIG. 6

Excess WOB.

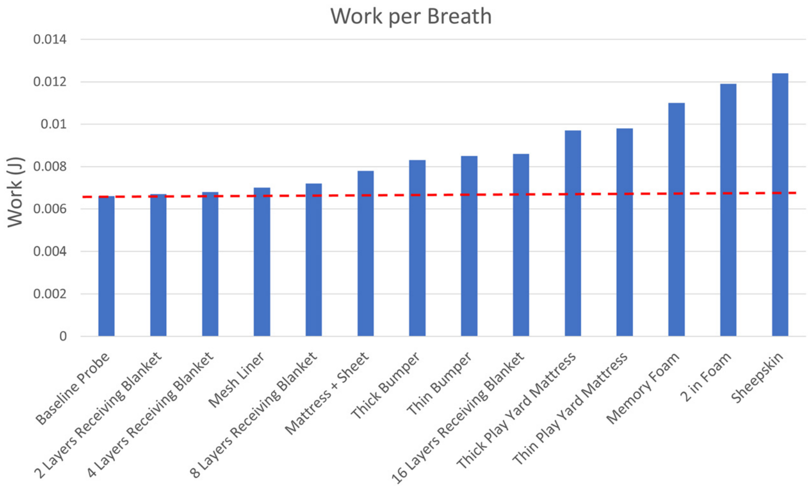
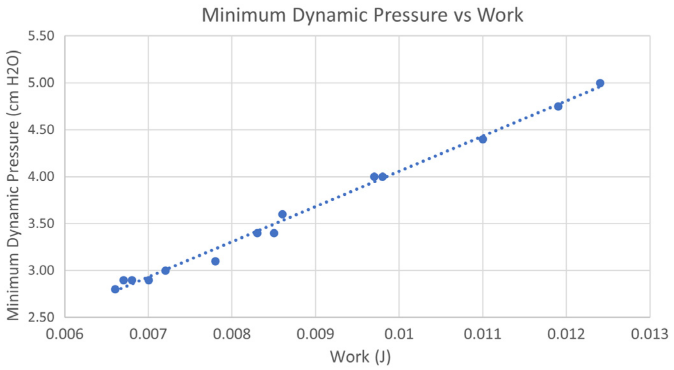


FIG. 7

Minimum pressure versus calculated work.



Static Airflow Resistance Measurements

A simpler alternative test method measures the pressure differential caused by application of the probe onto a test surface under the same 10 N load as the dynamic test. A fixed flow rate of 2 LPM suction is established through the probe and the pressure differential is recorded. The flow schematic is shown in figure 8.

Static Versus Dynamic Testing

Dynamic testing requires a breathing machine and pressure indicating instrumentation. Static airflow resistance testing requires only the probe, a flowmeter, and manometer, and is easier to perform. Figure 9 compares static and dynamic methods for measuring airflow resistance.

Comparing the static airflow measurement with the calculated WOB in figure 10, we find that a simple measurement of static airflow resistance is a reasonable proxy for WOB.

FIG. 8

Flow schematic.

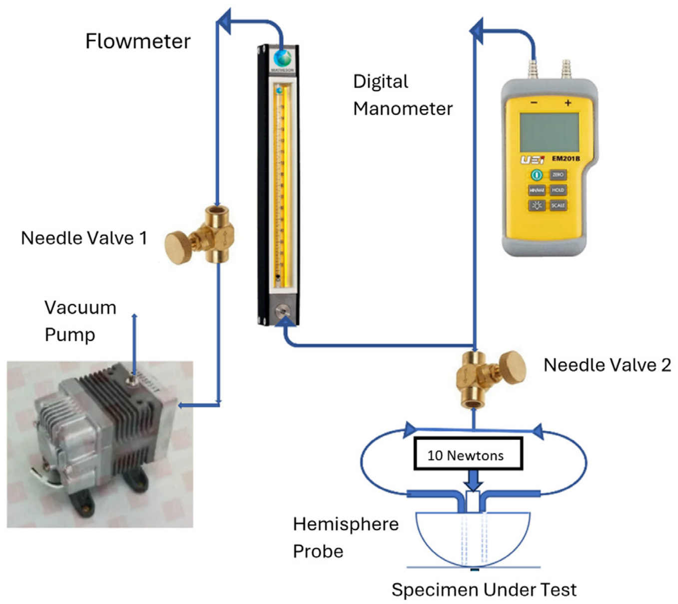


FIG. 9

Static versus dynamic airflow resistance.

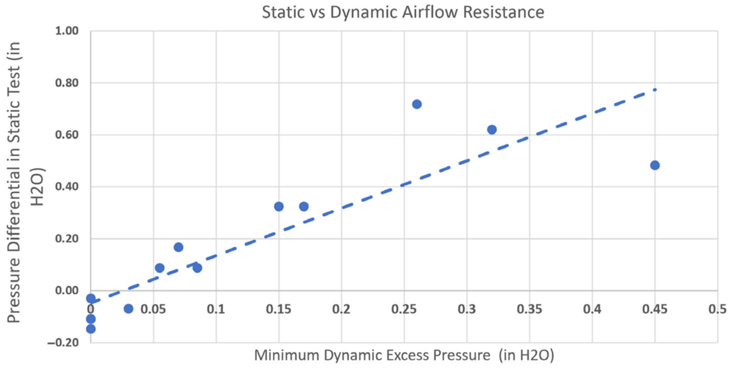
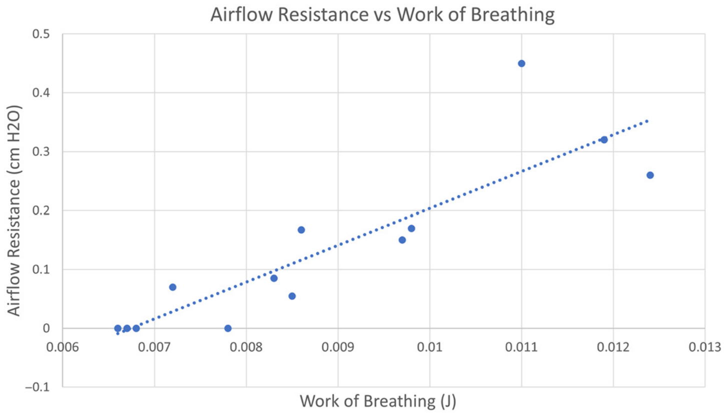


FIG. 10

Static airflow resistance versus WOB.



Figures 11–13 illustrate the relationships among CO_2 rebreathing, airflow resistance, WOB, and O_2.

Three types of foam with different levels of firmness were evaluated for airflow resistance. **Figure 14** illustrates the relationship between firmness and airflow resistance for these materials.

FIG. 11

Relationship between CO_2 rebreathing and airflow resistance.

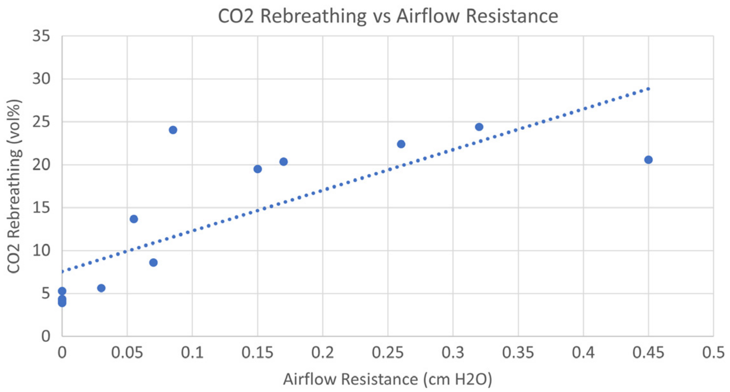


FIG. 12

Relationship between CO_2 rebreathing and calculated WOB.

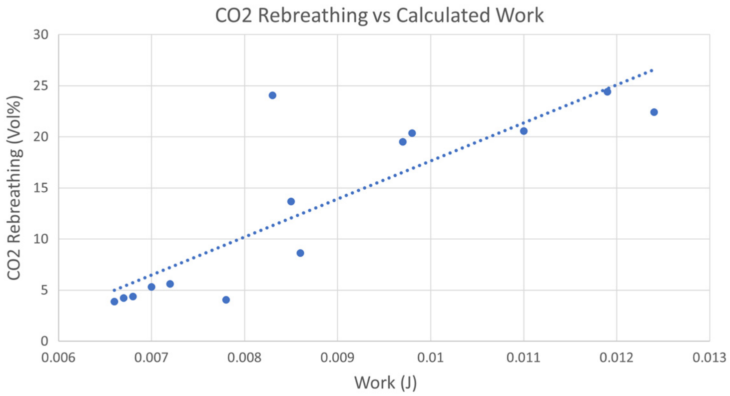


FIG. 13

Relationship between CO_2 and O_2.

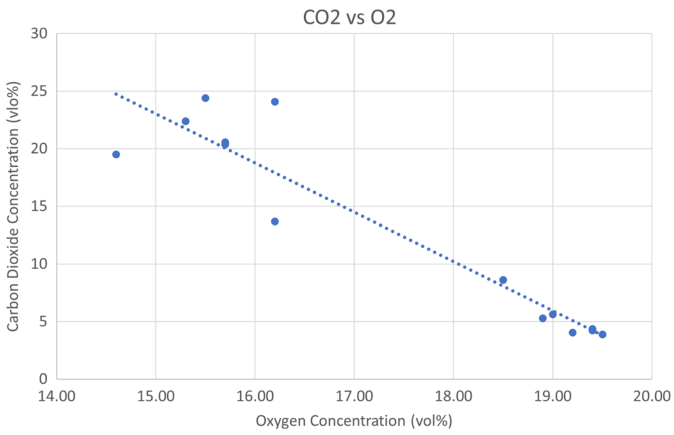
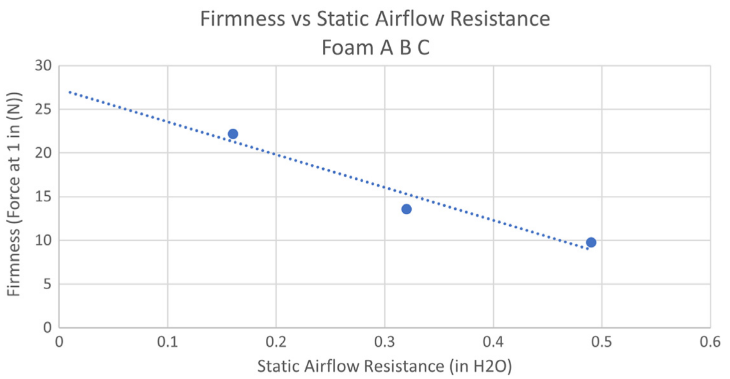


FIG. 14

Effect of firmness on airflow resistance.



Discussion

For infants, factors that increase respiratory effort (WOB) risk overwhelming their energy reserves and physical limitations. Whether this occurs acutely or over a longer time period would depend upon the severity of the insult. A measurement to approximate the severity is the static airflow test method.

Measuring WOB is made easier using the "shortcut" displayed in **figure 7**. Determining the minimum pressure during the inhalation portion of the cycle is sufficient to quantify differences in the work of breathing, without measuring the dynamic volume. Even simpler to perform, the static airflow test is a reasonable proxy for WOB as illustrated in **figure 10**.

In the context of product development, measurement of the static airflow resistance will quickly identify whether a material will have a greater or lesser effect on WOB. Inspection of **figures 9–14** illustrates the interrelationships among WOB, CO_2 rebreathing, static airflow resistance, and firmness. Each affects the others and measurement of all can provide a more complete understanding than any one measurement alone. Products made from a composite of materials present opportunities to minimize WOB and rebreathing simultaneously by using the aforementioned test methods.

When considering airflow resistance and its relevance to safety, it is important to differentiate between "breathability" for the baby and "breathability" of the bedding. Ideally, we would like the infant's exhaled breath to escape easily into the environment without excessive resistance. Further, we would like to prevent the exhaled breath from being accumulated within the bedding and returned during inhalation.

When designing products to be used in the infant environment, it is important to be mindful of the multiple potential hazard mechanisms believed to cause harm. Understanding the hazards will help to prevent the harms.

Conclusions

1. WOB increases with increasing airflow resistance.
2. Changes in WOB can be quantified by observing changes in minimum pressure during the breathing cycle.
3. It is desirable to reduce and minimize WOB by reducing airflow resistance at the infant/bedding interface.

References

1. R. Y. Moon, R. F. Carlin, I. Hand, The Task Force on Sudden Infant Death Syndrome, and the Committee on Fetus and Newborn, "Evidence Base for 2022 Updated Recommendations for a Safe Infant Sleeping Environment to Reduce the Risk of Sleep-Related Infant Deaths," *Pediatrics* 150, no. 1 (July 2022): e2022057991, https://doi.org/10.1542/peds.2022-057991
2. J. Huang, H. Zhang, M. Zhang, X. Zhang, and L. Wang, "Reference Values for Resistance and Compliance Based on the Single Occlusion Technique in Healthy Infants from Southeast China," *Journal of Thoracic Disease* 8, no. 3 (March 2016): 513–519, https://doi.org/10.21037/jtd.2016.02.69
3. J. N. Carleton, A. M. Donoghue, and W. K. Porter, "Mechanical Model Testing of Rebreathing Potential in Infant Bedding Materials," *Archives of Disease in Childhood* 78, no. 4 (April 1998): 323–328, https://doi.org/10.1136/adc.78.4.323
4. M. D. Leshner, "Forensic Engineering Evaluation of CO_2 Re-breathing in Infant Bedding Materials," *Journal of the National Academy of Forensic Engineers* 29, no. 2 (December 2012): 23–30, https://doi.org/10.51501/jotnafe.v29i2.771
5. M. R. Maltese and M. Leshner, "Carbon Dioxide Rebreathing Induced by Crib Bumpers and Mesh Liners Using an Infant Manikin," *BMJ Paediatrics Open* 3, no. 1 (April 2019): e000374, https://doi.org/10.1136/bmjpo-2018-000374
6. Y. Lee and W. Lim, "Shoelace Formula: Connecting the Area of a Polygon and Vector Cross Product," *Mathematics Teacher* 110, no. 8 (April 2017): 631–636, https://doi.org/10.5951/mathteacher.110.8.0631