The Raised Volume Rapid Thoracoabdominal Compression Technique

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Periodically, the Joint American Thoracic Society/European Respiratory Society Working Group on Infant Lung Function Testing publishes results of workshops on new techniques for lung function testing in infants. One such half-day workshop on forced expiratory flow-volume curves from raised lung volumes in infants was held by the Infant Lung Function Joint Working Group of the ATS and ERS immediately prior to the 1997 Annual Meeting of the American Thoracic Society in San Francisco. The workshop was organized by Monika Gappa and Julian Allen. Because there has been growing interest in this field since this workshop was held, a summary of this meeting, including some discussion of the physiology underlying these measurements, is now presented. A number of publications stemming from work presented during this workshop have either recently appeared or are in press. The purpose of this workshop was to help clarify discrepancies between different centers and facilitate subsequent development of standards that are necessary before this new approach of assessing airway function in infants and young children can be used widely as a clinical tool.

In adults and school children, forced expiratory flow-volume curves over the full lung volume range have been used for many years to assess airway function. In infants, the rapid thoracoabdominal compression (RTC) technique was developed to obtain partial forced expiratory flow-volume curves (1, 2). In this technique, an inflatable vest around the infant's chest and upper abdomen is rapidly pressurized at end inspiration, leading to a sudden forced expiration. Measurement of flow by a pneumotachograph attached to a face mask and integration to volume yield a partial forced expiratory flow-volume curve. Although this technique has yielded important information on airway physiology and pathophysiology in this age group, several disadvantages have become apparent. First, airway function is assessed in the tidal volume range only. Second, maximal flow at FRC ($\dot{V}max_{FRC}$) is highly variable; this is at least in part explained by the dynamically maintained functional residual capacity in infants such that there is no reliable volume landmark. Third, flow limitation is difficult to ascertain, especially in healthy infants.

Recently, the raised volume rapid thoracoabdominal compression (RVRTC) technique has been developed, in which the infant's lungs are inflated to a given airway pressure, using an external gas source (3) with or without an expiratory valve system (4, 5), before forced expiration begins. Available data are still sparse, but initial experiences with this modified technique have been promising. This is an exciting development because, for the first time, it is possible to generate flow-volume curves in infants that closely resemble flow-volume curves in older children and adults.

By inflating the infant's lungs several times above functional residual capacity, a short apnea can potentially be induced by two mechanisms. First, apnea can follow a minimal drop in P_{CO_2} due to augmented ventilation and second, relaxation of respiratory muscles can occur by induction of the Hering-Breuer inflation reflex, which is stronger at high volumes. This induced apnea makes respiratory muscle activity during the forced expiratory maneuver less likely to interfere with the measurement.

One important advantage of this technique is that the lung volume from which the forced expiration occurs can be standardized to a given pressure, potentially enabling comparisons within individual infants or between infants. Standardized inflation pressures may not achieve the same percentage of total lung capacity (TLC) in all infants; the degree of inflation will be influenced by changes in respiratory system compliance due to growth or disease. While it cannot be assumed that a given inflation pressure will achieve a certain percentage of TLC, the curves thus produced closely resemble conventional flow-volume curves obtained from total lung capacity, i.e., spirometry as performed by adults and schoolchildren. With this approach it seems possible to achieve flow limitation even in the absence of airway disease. Measurements of forced expiratory flows and volumes similar to those obtained in older, cooperative subjects, can be obtained. Since forced expiration is completed in less than 1 s in most infants, $FEV_{0.5}$, $FEV_{0.75}$, and FEF_{25-75} may be more useful measurements than FEV_1. Preliminary clinical data show a good correlation with disease severity. However, the most relevant measurement in this age group remains yet to be determined.

Because laboratories currently applying the RVRTC technique use different equipment and protocols, the joint ATS/ERS Infant Lung Function Working Group felt it was important to encourage exchange of ideas between different centers at this early stage, with the ultimate goal of consensus and standardization. Robert Castile (Columbus, OH), Peter LeSouëf (Perth, Western Australia, Australia), and Matthias Henschen (Institute of Child Health, London, UK) were asked to present their respective approaches with special emphasis on the equipment and currently unsolved problems.

The technical approach between centers varies. In Perth, a nebulizer pump controlled by a solenoid value system is used, in which the infant's lungs are automatically inflated by drawing air through the pneumotachograph and into the infant above the tidal volume range until a mouth pressure of 2 kPa (20 cm H_2O) or 3 kPa (30 cm H_2O) is reached (4-6). In Columbus and London, the raised volume is reached by actively inflating the infant's lungs several times (i.e., multiple inflation technique) to a preset pressure of 2 or 3 kPa (3, 7). This is achieved by connecting the face mask and pneumotachograph to a T-piece, which receives a constant airflow. Occlusion of the expiratory part of the T-piece results in lung volume increasing to the preset pressure; release of the occlusion allows expiration to proceed. It was felt that an inflation pressure higher than 3 kPa is impractical because of increasing problems due to leaks and shunting into the cheeks, upper airways, and stomach. The multiple inflation approach not only utilizes recruitment of the Hering-Breuer reflex, but also mild hyperventilation with end-tidal CO, dropping slightly.

There are a number of issues that need to be solved to allow measurements from different centers to be compared.

In contrast to forced expiratory maneuvers in the adult population, ***total lung capacity*** is probably not reached by the raised volume technique. Therefore, the inflation volume should be named according to the inflation pressure, i.e., V_{20}, V_{30}, etc. There is currently no agreement with regard to an appropriate terminology for the parameters derived (8).

The purpose of the RVRTC technique, as in conventional spirometry, is to measure flow at flow limitation. To use flow as a measure of airway size, flow limitation must be reproducibly obtained. A relatively invasive measure of flow limitation is the recording of isovolume pressure-flow (IVPF) curves, using an esophageal balloon or catheter. The driving pressure is increased stepwise and flows are determined at predetermined lung volumes. Flow limitation is reached when flow no longer increases with increasing driving pressure (transpulmonary pressure = esophageal − airway opening pressure).

The demonstration of flow limitation during the RVRTC maneuver has been inferred in different ways. In Columbus, an esophageal catheter was placed, and flow limitation demonstrated by the IVPF technique. Preliminary data from Columbus show that to reach flow limitation at 75, 50, and 25% expired volume, the transpulmonary (driving) pressures were 3.9 (SD 1.1), 2.9 (SD 1.0), and 1.8 (SD 0.7) kPa, respectively.

Indirect measurements of the driving pressures and determination of flow limitation were performed noninvasively in Perth and London. Static driving pressure was assessed without an esophageal catheter by determining alveolar rather than pleural pressures. The pressure measured at the airway opening during airway occlusion represents the elastic recoil pressure of the total respiratory system, which can be determined at varying lung volumes by repeated occlusion. During jacket inflation the total driving pressure available is equal to the sum of inflation pressure measured at the mouth, plus the transmitted compression pressure from the jacket itself to the alveolus. If the jacket is inflated during airway occlusion, the resultant rise in pressure at the airway opening represents the additional driving pressure available to force expiration, i.e., the pressure transmitted to the alveoli from the jacket. Airway occlusion followed by jacket inflation can be performed at end-tidal inspiration for the tidal RTC, or after inflation to a desired inflation pressure for the RVRTC technique.

Using this noninvasive technique, flow limitation is inferred by increasing driving pressure during the tidal RTC maneuver until $Vmax_{FRC}$ is reached. The same jacket pressure is then used during the RVRTC maneuver, since transmission at higher lung volumes following the inflation should be even higher because of increased chest wall compliance (6).

While it would be useful for centers to report driving pressure and percent transmitted jacket pressure in order to eliminate intersubject and intercenter differences in jacket design and method of application, it should be noted that it is not essential to know the driving pressure if flow limitation can be shown to have been reached. Such driving pressures are not routinely measured in conventional spirometry.

The group reached a working consensus that a driving pressure of about 4 kPa (40 cm H_2O), i.e., an inflation pressure of 2-3 kPa (20-30 cm H_2O), plus a transmitted jacket pressure of 2 kPa (20 cm H_2O) should suffice to achieve flow limitation throughout most of the expiratory maneuver. Robert Castile pointed out, however, that at high lung volumes it might be impossible to achieve flow limitation without driving pressures higher than 4 kPa.

Data were presented by Matthias Henschen to show that the rapid respiratory rate, and strong respiratory reflexes of newborn and preterm infants, present a challenge when attempting to apply the raised volume technique to this age group. Less reproducible results may be obtained in this population when using conventional analyses based on forced expiratory flows at fixed time intervals or proportions of expired volumes, since even after inflation to preset pressures, expired volume can be highly variable. Even after multiple inflations, very young infants rarely expire to residual volume. Since forced expiration is usually complete by 0.5 s in such infants, calculation of values such as $FEV_{0.75}$ and FEV_1 are not feasible. Furthermore, results are highly dependent on the preset pressure and the proposed inflation pressure of 3 kPa, commonly used in older infants, seems inappropriately high in these small, immature infants. A possible solution for addressing some of these problems, proposed by Matthias Henschen, was to calculate forced expiratory flows at fixed intervals above the infant's elastic equilibrium volume (i.e., the relaxed volume of the respiratory system as determined by the passive mechanics of the lung and chest wall). The elastic equilibrium volume in this approach is determined by extrapolating the descending limb of the passive expiratory flow volume to the intersection with the volume axis. This approach needs further validation (e.g., determining what happens if the respiratory system cannot be represented by a single time constant) but could facilitate interpretation of results in this difficult age group as well as comparison of results between different centers, where different methodology and, especially, different inflation pressures are employed (7).

Finally, regarding patient safety when applying this new technique, between the participants several hundred measurements have been performed in a wide range of infants in which no unwarranted side effects such as pneumothorax, respiratory insufficiency, or gastrointestinal problems have been observed. Despite the use of sedation no episodes of apnea or hypoxia due to hypoventilation following the raised volume maneuver have been reported.

One major issue remained unresolved following this preliminary workshop: While the system documenting flow limitation at FRC as used in Perth allows standardization of the measured pressure-flow relationship for comparisons within and between infants, it does not necessarily mean that flow limitation has been reached during the RVRTC maneuver, although this has been suggested by subsequent studies (9). The multiple inflation approach, as presented by Robert Castile, relies on flow limitation, which may be reached in different children at different applied pressures. If flow limitation is reached during the forced expiratory maneuver, the resulting flow-volume curve will reflect the pathophysiology of the airway. However, it remains to be proven, whether it is essential to reach flow limitation in order to obtain clinically useful information when using forced expiratory flow-volume curves from raised lung volumes.

Although preliminary normative data from a relatively large number of healthy infants and young children have been presented (10), no intercenter comparisons have validated the use of these data beyond the specific equipment used in the laboratory where these measurements have been performed.

In conclusion, available data suggest that the raised volume rapid thoracoabdominal compression technique is safe to use and may provide further insight into respiratory physiology in infants. It may yield more reproducible results in a wide age range of infants than the tidal forced expiratory flow-volume curves and may link with conventional forced expiratory maneuvers in cooperative children and adults to allow true longitudinal assessment of airway function in health and disease. However, use of the RVRTC technique as a routine clinical tool should remain restricted until standards have been developed and appropriate reference values have been established (11). Before then it is unlikely that a commercial system will become available to facilitate more widespread use of the technique.

Co-chairs: **Julian Allen and Monika Gappa**

Invited **participants: Julian Allen, Robert Castile, Monika Gappa, Matthias Henschen, Peter LeSouëf, John McNamara, Wayne Morgan, Mohy Morris, Howard Panitch, Michael Silverman, Peter Sly, Janet Stocks, and Robert Tepper.**

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