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One-Lung Ventilation: Which Lung Should Be PEEPed?

POSITIVE END-EXPIRATORY PRESSURE (PEEP) was introduced into clinical practice fifteen years ago,[1] and has proven to be a rapid and relatively high-benefit low-risk method for increasing the oxygenation capability of severely diseased lungs. The most accepted mechanism by which PEEP is thought to be of benefit is that PEEP causes an increase in lung volume at end-expiration [by definition, the functional residual capacity (FRC)]. The increase in FRC contributes to the prevention of airway and alveolar closure at end-expiration and to the recruitment of airways and alveoli during inspiration. The increases in lung volume and airway and alveolar openings result in increases in lung compliance, ventilation, and the ratio of ventilation-to-perfusion. An accepted risk of PEEP is that the PEEP-induced increase in lung volume can cause compression of the small intra-alveolar vessels. If the PEEP-induced intra-alveolar vessel compression is geographically widespread, then total pulmonary vascular resistance increases and cardiac output decreases. If the intra-alveolar vessel compression is limited to a region of the lung, then regional pulmonary vascular resistance increases and blood flow is diverted away from the PEEPed area.

One-lung ventilation is used commonly in patients undergoing thoracic surgery in the lateral decubitus position. In this position, the ventilated dependent (down) lung usually has a reduced lung volume (FRC) due to the combined factors of induction of general anesthesia and paralysis, and severe and circumferential compression by the mediastinal and abdominal contents and well-intentioned but inevitably suboptimal positioning effects (rolls, packs, shoulder supports).[2-5] Since the ventilated lung often has a decreased lung volume during one-lung ventilation, it is not surprising that several attempts have been made to improve oxygenation by treating the ventilated lung with PEEP. However, as nicely demonstrated by Katz *et al.* in this issue of ANESTHESIOLOGY,[6] and by other previous related studies,[7-11] the selective application of PEEP to the ventilated lung has had variable and directionally opposite (good and bad) effects on oxygenation, and at first glance seems to contradict the prediction of good results by the above simple lung volume theory.

Why should selective PEEP to the ventilated lung during one-lung ventilation sometimes improve and sometimes fail to improve oxygenation? As explained by Katz *et al.*[6] the net result of this particular distribution of PEEP on oxygenation should be a summation of both beneficial and harmful effects. The beneficial effects of selective ventilated lung PEEP can be presumed to have been present in these experiments on the basis of previously demonstrated increases in lung volume and the ventilation-to-perfusion relationship in the single ventilated lung (especially if it was dependent).[4,5] The harmful effects of selective ventilated lung PEEP can be presumed to have been present in these experiments on the basis of previously demonstrated increases in the pulmonary vascular resistance of the ventilated and PEEPed lung which caused diversion of blood flow away from the ventilated lung to the nonventilated lung.[7,12] Thus, the various one-lung ventilation-PEEP studies have had patients who have had an increase,[6,8] no change,[6,9,10] or a decrease[6,8,11] in oxygenation. The study by Katz *et al.*[6] was additionally concerned with the interaction of changes in ventilated lung PEEP and tidal volume and obtained results which further confirm the one ventilated lung volume vs. vascular resistance hypothesis. Although in none of these studies was a dose (ventilated lung PEEP)–response (Pa_{O_2}, $\dot{Q}_S/\dot{Q}_t$ value) relationship described, it seems reasonable to postulate on the basis of these results that the therapeutic margin of ventilated lung PEEP is quite narrow.

What would happen to oxygenation during one-lung ventilation if PEEP was applied selectively to the nonventilated (up) lung during one-lung ventilation? Since under these conditions the nonventilated lung is only

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slightly but constantly distended by oxygen (no inspiration or expiration), a better term for this ventilatory pattern arrangement would be nonventilated lung continuous positive airway pressure (CPAP). Recently, two reports, one in humans[11] and one in dogs,[13] have shown that the application of CPAP (without tidal ventilation) to only or just the nonventilated lung significantly increased arterial oxygenation. The latter study was performed with the dogs in the lateral decubitus position and showed that low levels of CPAP (5–10 cmH_2O) to the nonventilated, nondependent lung increased Pa_{O_2} and decreased shunt, while blood flow to the nonventilated lung remained unchanged. Therefore, low levels of CPAP simply maintained the patency of nondependent lung airways allowing some oxygen distention of the gas exchanging alveolar space in the nondependent lung. On the other hand, 15 cmH_2O of CPAP caused similar Pa_{O_2} and shunt changes while blood flow to the nondependent noventilated lung decreased significantly. Therefore, high levels of nonventilated lung CPAP act by permitting oxygen uptake in the nonventilated lung as well as by causing blood flow diversion to the ventilated lung where both oxygen and carbon dioxide exchange can take place. Since low levels of nonventilated lung CPAP are as efficacious as high levels of nonventilated lung CPAP and have less surgical performance and hemodynamic implications, it is logical first to use low levels of nonventilated lung CPAP. In both human[11] and dog[13] studies oxygen insufflation at zero airway pressure did not significantly improve Pa_{O_2} and shunt, and this result was probably due to the inability of zero transbronchial airway pressure to maintain airway patency.

In theory, and from the above considerations, it seems that the best treatment or way to improve oxygenation during one-lung ventilation is the application of differential lung PEEP or PEEP/CPAP. In this situation, the ventilated lung is PEEPed in the usual conventional manner in an effort to improve ventilated lung volume and ventilation-to-perfusion relationships. Simultaneously, the nonventilated lung receives CPAP in an attempt to improve oxygenation of the blood perfusing the nonventilated lung. Therefore, with differential lung PEEP or PEEP/CPAP, it does not matter where the blood flow goes nearly as much as during simple one-lung ventilation since wherever it goes (either ventilated or nonventilated lung) it has at least some chance to participate in gas exchange with alveoli that are oxygen expanded. In support of this contention, oxygenation has been increased significantly in patients during thoracotomy in the lateral decubitus position when PEEP has been added to the ventilated dependent lung, while the nondependent lung was also able to participate in gas exhange by virtue of being ventilated at zero end-expiratory pressure (ZEEP).[14]

In fact, there are now multiple reports of significant increases in oxygenation obtained with the application of differential lung ventilation and end-expiratory pressure (either PEEP/PEEP, PEEP/CPAP or CPAP/CPAP) through double-lumen tubes to patients in the intensive care unit with acute respiratory failure due to predominantly unilateral lung disease.[15-20] In all cases conventional whole-lung therapy (mechanical ventilation, PEEP, CPAP) administered via a standard single-lumen tube either failed to improve or actually decreased oxygenation. In most cases the amount of PEEP initially administered to each lung was inversely proportional to the compliance of each lung; presumably and ideally this PEEP arrangement should result in equal FRC in each lung. In some cases, the amount of each lung PEEP was later readjusted and titrated in an effort to find a differential lung PEEP combination that resulted in the lowest right to left transpulmonary shunt. The present state of the art with differential lung PEEP and tidal ventilation has advanced to the point where special equipment has been developed to facilitate the application of this form of respiratory therapy.[11,18,21,22]

In conclusion, the present study by Katz *et al.*,[6] combined with those studying selective up lung PEEP[11,13] and differential lung PEEP,[15-20] suggest that the sequence of treating severe hypoxemia during one-lung ventilation in the lateral decubitus position should be to cautiously apply 5–10 cmH_2O of PEEP to the ventilated dependent lung. If oxygenation does not improve, 5–10 cmH_2O of CPAP to the nonventilated nondependent lung should then be applied. If this does not improve oxygenation, dependent lung PEEP should be increased to 10–15 cmH_2O of PEEP while the nondependent lung is maintained at 5–10 cmH_2O of CPAP. In this way a search for the maximum compliance and a minimum right-to-left transpulmonary shunt might be started, in an attempt to find the optimal end-expiratory pressure for each lung and the patient as a whole.

JONATHAN L. BENUMOF, M.D.
Associate Professor Of Anesthesia
University of California, San Diego
Anesthesia Research Laboratory T-001
La Jolla, California 92093

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