Safety and efficacy of lung recruitment maneuvers in post-operative pediatric cardiac surgical patients

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Abstract

Objective: To demonstrate the safety of lung recruitment maneuvers in post-operative pediatric cardiac surgical patients. To assess the ability of lung recruitment maneuvers to improve lung function. *Hypothesis:* We hypothesize that ventilator recruitment strategies be well-tolerated in cardiac patients, and that they may benefit such patients by improving physiologic variables such as lung function and oxygenation.

Methods: Sixty-two pediatric post-operative cardiac surgical patients were randomly selected to include in this retrospective chart review. Study subjects were selected from all patients who met inclusion criteria in the year immediately following implementation of a lung recruitment protocol in a local free-standing pediatric hospital. Physiologic variables before, during, and after lung recruitment were recorded as well as patient demographics, diagnoses, morbidities and mortality. *Results:* A statistically significant increase in dynamic compliance of the lungs and renal non-invasive regional oximetry was noted immediately after each recruitment maneuver. There was no statistically significant change in blood pressure, heart rate or oxygen saturation during the maneuvers. There was a transient increase in central venous pressure during the maneuvers (average increase < 1 mmHg). Of the 62 patients, there were 7 cases of pneumonia and 5 cases of small pneumothorax, often resolving without intervention. *Significance:* Demonstrating recruitment maneuvers are safe in pediatric patients with cardiac disease will allow practitioners to confidently utilize them when caring for ventilated patients. Such patients may benefit from potential improvements in lung function and decreased ventilator-associated morbidities.

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Introduction/Significance:

Post-operative mechanical ventilation is often required for children who have undergone surgical repair for congenital cardiac disease. Sound ventilator management is imperative for this population. These patients have an already compromised physiologic status and therefore may be less equipped to effectively cope with the physiologic challenges that inevitably come with surgery and in the post-operative period. The goals of mechanical ventilation are to ensure adequate gas exchange as well as to reduce, as much as possible, any ventilation-associated lung injury. It is thought that much of ventilator-induced lung injury arises from the repetitive collapse (atelectasis) and re-expansion of the alveoli (1). Efforts to maintain the alveoli in an open, ventilated state help reduce alveolar stress and lung injury.

There are effective maneuvers that physicians and respiratory therapists utilize to ensure continuing patency of the alveoli. Such maneuvers are typically known as alveolar recruitment maneuvers, or more simply, lung recruitment. Although there are many different techniques utilized to perform such maneuvers, the concept is generally the same and fairly intuitive – 'recruit' as many of the alveoli as possible so they may participate in gas exchange. Along with better aeration, maintaining patency reduces atelectatic areas and decreases lung injury. Decreased atelectasis is thought to improve lung compliance and improve arterial oxygenation, which could potentially decrease the work on the heart (2-6).

A select number of studies have been done in pediatric populations to determine whether these maneuvers are safe, if they reduce the degree of lung collapse, and if they improve oxygenation. One such study demonstrated the ability of lung recruitment to reduce atelectasis in children without cardiac disease, who required general anesthesia for MRI (7). Another study showed that lung recruitment improved oxygenation, ventilation and lung compliance in children who were ventilated for acute lung injury (2).

Interestingly, studies on recruitment maneuvers in children with cardiac disease are virtually nonexistent because of the concern of the possible detrimental effects on hemodynamics during the maneuver. We did find one study that looked at recruitment maneuvers in pediatric post-operative cardiac patients. The study looked at the effect of a single recruitment maneuver in each of twenty patients. Although it demonstrated a statistically significant improvement in dynamic compliance of the lungs, the PaO2/FiO2 ratio and end-expiratory lung volume, they excluded children with residual intracardiac shunting, hemodynamic instability, valve regurgitation and respiratory failure. In addition to the relatively low patient number included in the study, as well as the fact each patient only had one maneuver regardless of length of intubation, it is difficult to ascertain the long-term safety and possible benefits that repeated lung recruitment would provide.

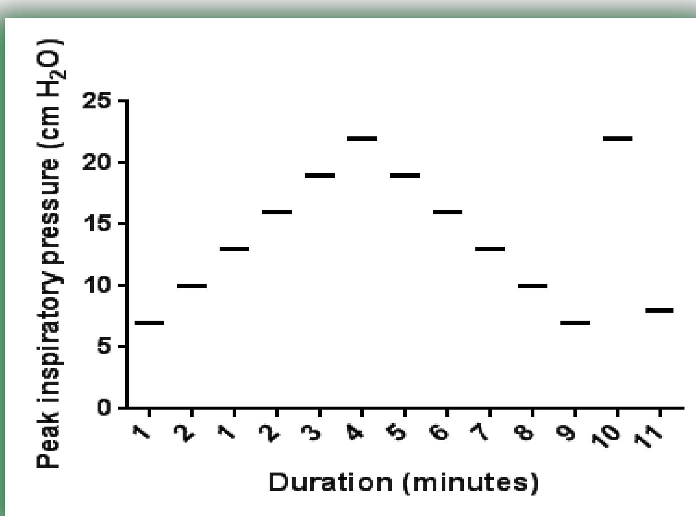
Our overall goal was to demonstrate the safety and tolerability of recruitment maneuvers in a large population of children with congenital heart disease. In addition to a larger sample size, we studied the effects of multiple recruitments on each patient throughout the duration of their ventilator dependence. In order to determine safety we analyzed heart rate, respiratory rate, blood pressure, central venous pressure and oxygen saturation before, during and after recruitment. In addition, we examined changes in inotrope and vasopressor requirement before, during and after each maneuver. Efficacy of recruitment was assessed by determining changes in the dynamic compliance of the lungs, oxygen saturation index and regional oximetry. We also determined the incidence of pneumonia, pneumothorax, the length of intubation and hospital stay as well as overall mortality to further assess safety and possible benefits of recruitment maneuvers.

The demonstration of the safety and efficacy of lung recruitment maneuvers would be of great benefit to the management of these challenging patients. We show that incorporating lung recruitment in the ventilatory management of pediatric post-operative cardiac surgical patients can improve lung function, reduce ventilator-dependent days, and reduce ventilator-associated morbidities, without significantly affecting hemodynamics.

Research materials and methods:

We conducted a retrospective chart review at a local pediatric hospital after obtaining IRB approval. A patient list was generated by the information technology department that included all pediatric patients who underwent cardiac surgery in the year following implementation of the lung recruitment protocol. We included all patients under the age of eighteen who underwent open heart surgery and had lung recruitments performed post-operatively. We excluded patients with tracheostomies.

Recruitment protocol: Lung recruitments were performed either by a respiratory therapist or the attending physician. The ventilator mode was set to pressure control and was adjusted to reach a tidal volume of 6cc/kg. The PEEP (positive end-expiratory pressure) was set above closing pressure by increasing PEEP gradually to 5-10cm H2O above baseline PEEP. PEEP was increased in 1-2cm H2O intervals and each increase was sustained for one minute. Tidal volume was recorded with each increase in PEEP. PEEP was increased until the tidal volume stopped increasing. When the tidal volume started decreasing, PEEP was decreased by 1-2cm H2O, once again waiting one minute after each decrement. This was done until derecruitment was noted. Derecruitment was recognized as a significant decrease in tidal volume with a small decrease in pressure level or a large decrease in dynamic compliance. The PEEP level before collapse was noted. PEEP was again increased to the pre-lung derecruitment level, plus 5-10cm H2O. It was then brought back down to 2-4cm H2O above the derecruitment level. The patient was then placed back on the original mode of ventilation with the PEEP adjusted to the optimal PEEP determined by the maneuver. On average, recruitment occurred in four hour intervals but was repeated sooner if there was a loss of PEEP or a ventilator disconnection *(graph 1)*.



Graph 1.

Recruitment protocol: Example of average recruitment maneuver. PEEP starts typically between 5 – 10 mmHg and is increased in 1 – 2 mmHg increments and held for 1 minute until a maximum PEEP is reached. PEEP is decreased incrementally then raised to max PEEP and brought down to new PEEP.

A database was generated and 62 patients were selected at random to analyze. We collected demographic data consisting of age, diagnosis, associated anomalies/chromosomal abnormalities and the type of surgical procedure. We recorded several possible outcomes which included pneumonia and pneumothorax incidence, length of intubation, length of hospital stay, length of oxygen requirement after extubation, use of oxygen after discharge, chest x-ray evidence of bronchopulmonary dysplasia and death.

Physiologic variables were recorded by nurses and respiratory therapists before, during and after the procedure. We pulled data from a window of time that included the two hours preceding the maneuver, the time during the maneuver and two hours after the maneuver. For each variable we recorded the two measurements obtained closest to the period just before, during, and after recruitment. Since physiologic variables are dynamic, we averaged the two vital signs in each category in an attempt to minimize human error and provide a more accurate representation of the patient's status at the time of interest. Physiologic variables included blood pressure, heart rate, respiratory rate, oxygen saturation, saturation index, central venous pressure, regional oximetry and lung compliance. Ventilator data was collected and included: duration of maneuver, peak pressure and PEEP. In addition we noted the presence and dose of inotropes and vasoactive infusions before, during and after each maneuver, as well as the use of nitric oxide.

Since lung recruitment maneuvers temporarily increase intrathoracic pressure, theoretically reducing venous return to the heart, we analyzed their effect on blood pressure, heart rate and central venous pressure to determine tolerability and safety. In addition, we reported any changes in inotrope requirement to further assess safety.

Results

A total of 62 patients who had open heart surgery and underwent lung recruitment in the year following implementation of a recruitment protocol were included in our analysis. Patients ranged from 6 days to 9 years of age with a median age of 3 & 1/2 weeks at the time of open heart surgery. The median weight was 4 kilograms with a range from 2 to 36 kilograms. Median length of hospital stay was 18 days with a range of 5 to 82 days. Patients were intubated for a median of 3 days with a range of 1 to 15 days. There were 14 reintubations. All patients required oxygen after extubation and 20 patients were discharged with oxygen for home use. Among the 42 patients not discharged with oxygen there was a median in-patient oxygen requirement of 3 days post extubation, with a range of 2 to 27 days.

All patients had congenitally malformed hearts. There was a large variety of both diagnoses and surgical procedures in the patients studied. Among the 62 patients, 5 had a co-diagnosis of airway abnormalities including tracheomalacia and choanal atresia, 1 patient had midline defects and 3 patients had heterotaxy. There were 4 patients with DiGeorge syndrome. Pneumonia was diagnosed in 7 patients post-operatively, 5 of which had one or more re-intubations. Five patients developed a small pneumothorax that resolved in most patients in less than 24 hours without placement of a chest tube. There was no evidence on chest x-ray of bronchopulmonary dysplasia for any patient. There were 2 deaths *(tables 1-5).*

Lung recruitment was initiated in the immediate post-operative period for all patients. The frequency with which recruitments were performed varied among patients. Recruitment maneuvers were performed every 4 hours for most patients, but were repeated as often, or as little as needed to maintain optimal lung function. On a few occasions, lung recruitment was repeated in less than 4 hours. Conversely, some patients required maneuvers only once in a 24 hour period.

Table 1

Demographic details of 62 post-operative cardiac surgical patients undergoing ventilator recruitment

N = 62	
Median Age (in weeks)	3 & ½ weeks (range 1wk to 9 years)
Median weight (in kilograms)	4 kg (range 1.85kg to 36 kg)
Median BSA (body surface area)	.24m^2 (range .13 to 1.13m^2)
Total number of maneuvers	475
Average number of maneuvers per patient	8 (range 1 to 30)

Table 2

Type of surgical procedure(s). *NB many patients underwent multiple procedures in a single surgery.*

N = 62

Procedure	Number of patients
VSD/ASD closure	28
Repair of double outlet RV	2
Norwood & Bidirectional Glenn	5
PDA stent	3
Blalock-Taussig shunt	6
Pulmonary artery banding	5
Valvuloplasty	14
Arterial switch	10
Closure of AV canal	6
Orthotopic heart transplant	2
Repair of coarctation	9
Repair of tetralogy of Fallot	3
PDA ligation	6
SANO procedure	3
Lecompte procedure	2
Damus-Kaye Stansel procedure	1

Table 3

Diagnosis. *NB many patients had more than one diagnosis*

N = 62	Number of patients
Double outlet RV	3
Pectus carinatum	1
Bicuspid aortic valve	1
Double inlet left ventricle	1
Pulmonary stenosis	10
Hypoplastic left heart	9
Mitral stenosis	5
Aortic atresia	3
Transposition of the great vessels	11
TAPVR	5
Single RV	3
Tetralogy of Fallot	9
Aortopulmonary window	1
VSD/ASD	28
Coarctation of the aorta	10
Patent PDA	6
AV canal	6
Congestive heart failure	5
Pulmonary hypertension	1
Holmes heart	1
Shone complex	1
Ebstein anomaly	1

Table 4

Outcomes.

N = 62	Number of patients
Pneumonia	7
Pneumothorax	5
Patients with chest X-ray evidence of bronchopulmonary dysplasia	0
Patients discharged with home oxygen	20
Prolonged intubation (defined as >7 days)	9
Death	2
Average length of intubation	4 days
Median hospital stay	20 days

Table 5

Associated chromosomal anomalies/physical abnormalities

N = 62	Number of patients
Choanal atresia	1
Intestinal malrotation	1
Trisomy 21	6
Tracheomalacia	4
Heterotaxy	3
Chromosomal 8p23 deletion	1
DiGeorge	4
Myelomeningocele with Chiari II malformation	1
Absent left kidney	1
VACTERL	1
Dextrocardia	1
Unspecified chromosomal abnormality	1

Lung function: There was a statistically significant 31% increase in dynamic lung compliance following lung recruitment. The mean difference was .15mL/cmH2O/kg with each recruitment ($P < .0001$; 95% CI). The median compliance prior to each maneuver was .48 mL/cmH2O/kg followed by a median compliance of .63 mL/cmH2O/kg after. Dynamic compliance range before the maneuver was .18mL/cmH2O/kg to 1.4mL/cmH2O/kg and was .18mL/cmH2O/kg to 2 mL/cmH2O/kg after. All 62 patients experienced an increase in lung compliance immediately after the maneuver *(figure 1)*.

A paired t-test demonstrated a statistically significant increase in renal non-invasive regional oximetry (NIRS), from start to finish of recruitment ($P = .015$). Average value prior to maneuver was 69, with an average of 70 immediately after. Range before was 15 to 95 and after was 15 to 95 (*figure 2)*. There was no statistically significant change in cerebral NIRS from start to finish of recruitment ($P = .57$; 95% CI). The average cerebral NIRS before and after recruitment was 65 and 65, respectively, with a range of 22 to 95 before and 28 to 95 after *(figure 3).*

There was no statistically significant change in saturation index before or after recruitment ($P = .34$; 95% CI). Mean saturation index before recruitment was 4.98 and after was 4.93 *(figure 4)*.

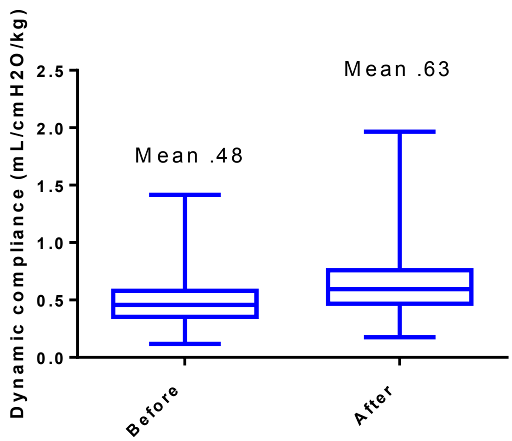


Figure 1.

Dynamic compliance before and after lung recruitment **(P < .0001; 95% CI).**

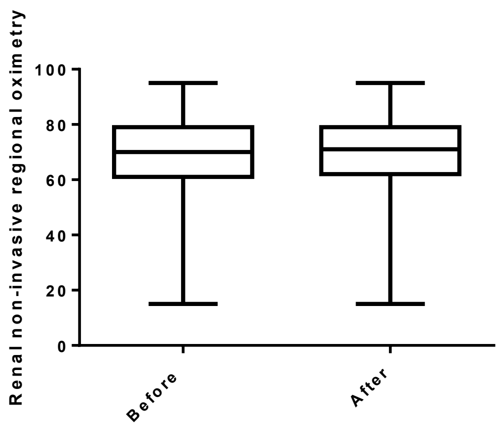


Figure 2.

Renal non-invasive regional oximetry before and after lung recruitment.Median value before recruitment = 70; median value after recruitment = 71 **(P = .015, 95% CI)**

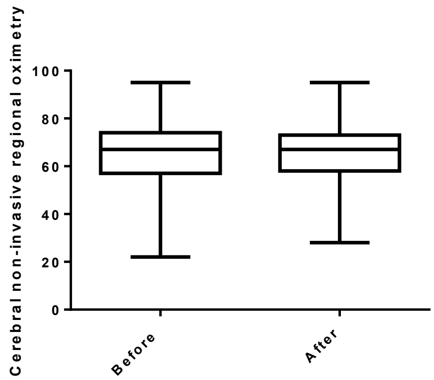


Figure 3.

Cerebral non-invasive regional oximetry before and after lung recruitment. Median value before recruitment = 67; median value after recruitment = 67 **(P = .56, 95% CI)**

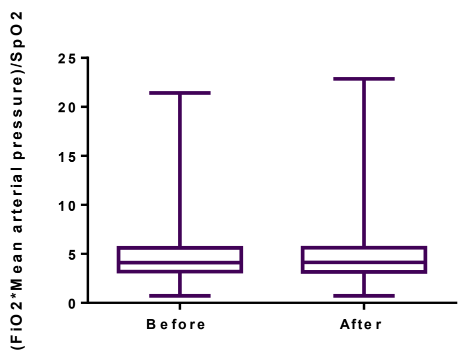


Figure 4.

Saturation index before and after recruitment. Mean value before recruitment 4.98; mean value after recruitment 4.9 (P = .34; 95;CI).

Safety of maneuvers: There were no statistically significant changes in heart rate and blood pressure from start to finish of each maneuver *(figures 5 & 6)*. The range for mean arterial pressure (MAP) was 35 to 89mmHg prior to maneuver with a median of 59mmHg; MAP range during maneuver was 34 to 92mmHg with a median of 59mmHg; MAP range after maneuver was 37 to 88mmHg with a median of 59mmHg. Heart rate before the maneuver ranged from 80 to 213bpm with a median of 138bpm; heart rate during maneuver ranged from 88 to 227bpm with a median of 139; after maneuver range was 80 to 226bpm with a median of 139bpm.

There was no statistically significant change in oxygen saturation before and after maneuvers ($P = .40$). The range was 63 to 100% before and 66 to 100% after. Average saturation before was 92% and after was 93% *(figure 7)*.

There was a transient, but statistically significant rise in CVP during procedure ($P = .02$; 95% CI). On average this rise in CVP was less than 1 mmHg. CVP range before was 6 to 26mmHg; during was 5 to 26mmHg; after was 4 to 31mmHg. The median CVP before, during and after was 12.24, 12.71 and 12.02mmHg, respectively *(figure 8)*.

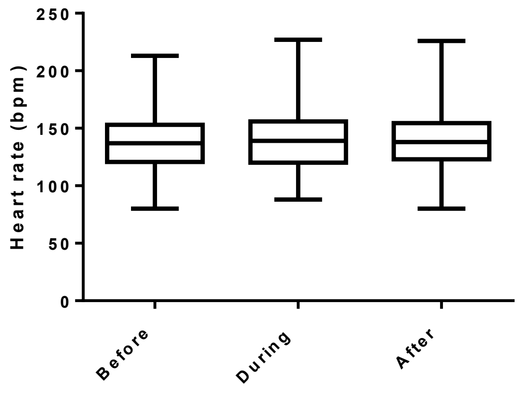


Figure 5.

Average heart rate before, during and after recruitment.

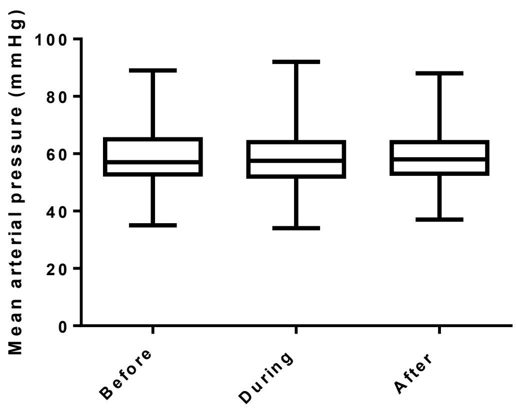


Figure 6.

Average blood pressure before during and after recruitment.

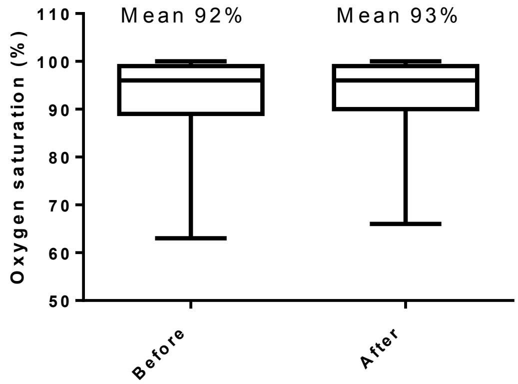


Figure 7.

Oxygen saturation before, during and after recruitment.

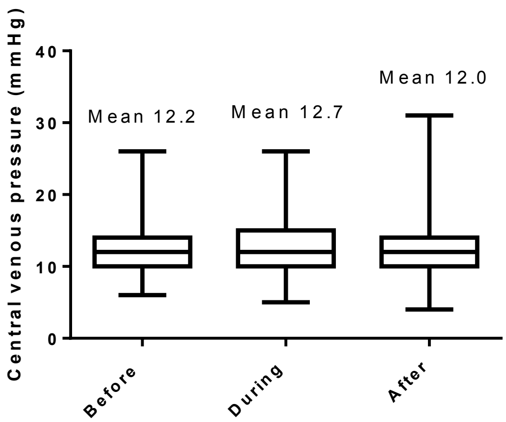


Figure 8.

Central venous pressure before, during and after recruitment.

Inotropic support requirements: There were a combined total of 475 recruitment maneuvers performed on the 62 patients we analyzed. Of the 475 maneuvers, there were 68 changes to inotrope dosage either before, during or after the maneuver. Of these 68 changes, 52 consisted of a decrease in dose and 16 resulted in an increase in dose. 407 (86%) maneuvers were performed without adjusting inotrope dose *(figure 9)*.

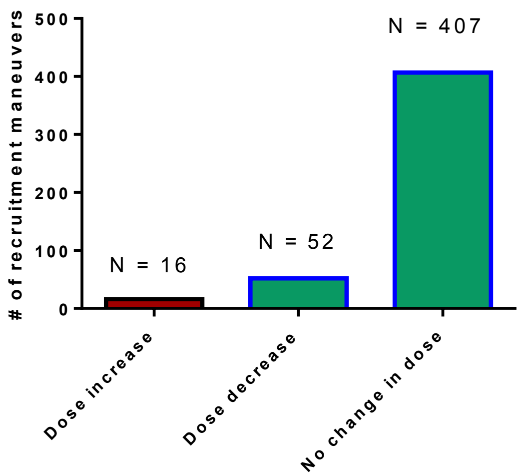


Figure 9.

Inotrope and vasoactive infusion data from all 475 maneuvers performed on our 62 patients. 16 maneuvers required a dose increase; in 52 maneuvers, patients tolerated a dose decrease and in 407 maneuvers there were no dose adjustments.

Discussion

We determined that use of lung recruitment maneuvers in post-operative pediatric cardiac surgical patients is an effective way to improve lung function as evidenced by significantly improved dynamic compliance of the respiratory system and improvement in renal non-invasive regional oximetry. In the absence of hyperinflation, improvement in dynamic compliance of the lungs is thought to be related to reduced areas of atelectasis (lung collapse) (1,8). Keeping the lung well inflated and aerated reduces alveolar collapse. Once the alveoli collapse, they require a greater pressure to inflate them once again (8). The repetitive collapse and reopening of the alveoli is thought to be related to increased lung damage (2). Performing regular recruitment maneuvers while patients are on ventilators, allows for better compliance of the lungs, thus reducing the amount of pressure required to inflate the lungs.

A theoretical concern of performing recruitment maneuvers, especially in patients with cardiac disease, is the potential impact they have on venous return and blood pressure. Possibly for this reason, there is not much data on lung recruitments in this patient population. In a study of 20 post-operative pediatric cardiac patients who underwent similar recruitment maneuvers, one or more fluid boluses were administered to each patient during their maneuver. Each patient had only one maneuver performed, regardless of their length of intubation, and a PEEP of 8cmH2O was used on every patient instead of recruiting to find the optimal PEEP as occurred in our study. While none of the patients experienced a significant difference in heart rate, mean arterial pressure and right atrial pressure throughout their maneuver, the use of fluid boluses in every patient makes it difficult to adequately assess the safety and tolerability of such maneuvers. In addition, there was no data on use of inotropes during lung recruitment (1).

While all 475 recruitments performed on our 62 patients were done after verifying hemodynamic stability from nursing staff and physicians, patients were not required to get standard fluid boluses for each maneuver. In addition, we recorded the use of all inotropes to assess whether dosage adjustments were required which might suggest the impact of maneuvers on patient hemodynamics. We found that performing lung recruitment maneuvers did not significantly affect heart rate and mean arterial blood pressure (MAP). There was no statistically significant change in these variables from start to finish of lung recruitment using a one-way ANOVA test. The effect on central venous pressure was small and transient and clinically inconsequential. There was no evidence of having to terminate any recruitment maneuvers prematurely in this study.

In addition to providing evidence recruitment strategies do not significantly affect hemodynamics, especially in the absence of required fluid boluses, we wanted to further address their tolerability by noting the use of inotropes. We included statistics on dopamine, epinephrine, calcium, milrinone and vasopressin use. Of the 475 maneuvers performed, 407 were conducted without any change to inotrope dose. During, or after 52 of the maneuvers (11% of the maneuvers), inotrope dose was decreased. In 16 of the maneuvers (3%), inotrope dose was increased. The fact that the vast majority of patients either had no inotrope adjustment or tolerated a decrease during or after their maneuver, suggests the overall safety and tolerability from a physiologic standpoint.

There was a statistically significant (P = .015; 95% CI) increase immediately after lung recruitment in cerebral non-invasive regional oximetry values. Mean prior to recruitment was 69; mean after was 70. There was no statistically significant change in oxygen saturation before or after maneuver.

In addition to a vastly larger number of recruitments studied, our research is unique among recruitment studies in pediatric cardiac surgical patients in that we had fewer exclusion criteria. In one study, infants were excluded if they had evidence of residual intracardiac shunt, were in any rhythm other than sinus rhythm, if they had valve regurgitation or respiratory failure. Our only exclusion criterion was the presence of a tracheostomy. Five of our patients had airway abnormalities, including tracheomalacia and choanal atresia. In addition, since residual intracardiac shunt or valve regurgitation were not exclusion criteria, it is possible patients had residual abnormalities after surgery, which could further demonstrate recruitment safety among these patients.

Another theoretical concern of applying recruitment strategies to ventilated patients is the possibility of causing pneumothorax from increased intrathoracic pressures. We are not aware of any studies which demonstrate an increased risk of pneumothorax among recruitment patients above which would be expected with mechanical ventilation in general. Interestingly however, a fairly large study of 74 patients with acute lung injury and pneumothoraces from trauma was conducted to observe the effect of early alveolar recruitment strategies on reducing hospital stay and improving lung function. After the pneumothoraces were properly evacuated, alveolar recruitment strategies were begun up to 5 times per day. No redevelopment of pneumothorax occurred among the patients and there was a statistically significant decrease in length of admission, an improvement in oxygenation and an increase in dynamic compliance. The study was conducted in patients with known, albeit treated, pneumothoraces along with acute lung injury in order to establish safety and allow these patients to benefit from early recruitment (9). Five of our 62 patients did develop a small pneumothorax, most of which resolved in less than 24 hours without intervention. With the size of our study population and lack of controls consisting of mechanically ventilated patients with similar demographics and diagnoses but without recruitment maneuvers, it is difficult to ascertain whether development of pneumothorax in 5 patients was related to the recruitment maneuvers. Comparing our numbers to national averages and/or including data on controls would help delineate any relationship between pneumothoraces and recruitment strategies that may exist.

Seven of our 62 patients developed pneumonia. Of these 7, 5 patients had been re-intubated one or more times. The criteria for diagnosis of pneumonia were clinician diagnosis, chest x-ray diagnosis or positive sputum culture. Since mechanical ventilation and ICU admission both increase the chances of developing pneumonia, it is difficult to say what effect recruitment strategies have on development of pneumonia, if any. In addition, re-intubation increases a patient’s risk for developing pneumonia. It is our hope that recruitment strategies decrease atelectasis which could potentially reduce risk of pneumonia. Including patient controls without recruitment or drawing from a national database could help distinguish any differences in pneumonia incidence with recruitment. However, since the diagnosis of pneumonia is often times largely clinically-based, objectivity of this diagnosis comes into question.

Future directions

In order to further evaluate the impact of recruitment on patient outcomes we plan to compare our data to national post-operative pediatric cardiac ICU averages.

Since lung recruitment maneuvers were not performed at set intervals among all patients, it is possible patients who had more regular recruitments performed benefited more than patients who underwent recruitment 1 or fewer times in 24 hours. Although not analyzed due to the paucity of data, we noted a possible improvement in oxygenation and lung function when recruitments were performed more regularly. Patients who had recruitments performed every 4 hours, then experience a large gap of time between maneuvers, seemed to require larger mean airway pressures to re-recruit the collapsed alveoli. This would be interesting but challenging to study, as there are arguably many variables which determine the frequency with which maneuvers were repeated. By noting the time intervals for recruitments it may be possible to uncover potential benefits of more frequent maneuvers.

Conclusions:

We demonstrated the efficacy of lung recruitment strategies in improving lung function as evidenced by significant improvements in lung compliance and renal non-invasive regional oximetry. Improvement in lung compliance reduces the amount of pressure needed to adequately ventilate the lungs which could potentially reduce damage to the lungs as well as avoid potential hemodynamic consequences of high intrathoracic pressure. Improved renal NIRS indicates better oxygenation likely due to more alveoli participating in gas exchange. Lung recruitment strategies were well tolerated by post-operative pediatric cardiac surgical patients, which demonstrates overall safety of such procedures. While 5 cases of pneumothorax did occur, they were clinically insignificant and most resolved in less than 24 hours without intervention. Central venous pressure transiently and slightly increased (<1 mmHg) during recruitment but mean arterial pressure and heart rate did not change significantly. In addition, inotrope requirement was decreased or stayed the same in the vast majority (97%) of patients, further indicating physiologic tolerability of recruitment maneuvers in cardiac patients.

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