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Clinical Investigations

'Alveolar recruitment strategy' improves arterial oxygenation during general anaesthesia

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Abnormalities in gas exchange during general anaesthesia are caused partly by atelectasis. Inspiratory pressures of approximately 40 cm H_2O are required to fully re-expand healthy but collapsed alveoli. However, without PEEP these re-expanded alveoli tend to collapse again. We hypothesized that an initial increase in pressure would open collapsed alveoli; if this inspiratory recruitment is combined with sufficient end-expiratory pressure, alveoli will remain open during general anaesthesia. We tested the effect of an 'alveolar recruitment strategy' on arterial oxygenation and lung mechanics in a prospective, controlled study of 30 ASA II or III patients aged more than 60 yr allocated to one of three groups. Group ZEEP received no PEEP. The second group received an initial control period without PEEP, and then PEEP 5 cm H_2O was applied. The third group received an increase in PEEP and tidal volumes until a PEEP of 15 cm H_2O and a tidal volume of 18 ml kg^{-1} or a peak inspiratory pressure of 40 cm H_2O was reached. PEEP 5 cm H_2O was then maintained. There was a significant increase in median Pa_{O_2} values obtained at baseline (20.4 kPa) and those obtained after the recruitment manoeuvre (24.4 kPa) at 40 min. This latter value was also significantly higher than Pa_{O_2} measured in the PEEP (16.2 kPa) and ZEEP (18.7 kPa) groups. Application of PEEP also had a significant effect on oxygenation; no such intra-group difference was observed in the ZEEP group. No complications occurred. We conclude that during general anaesthesia, the alveolar recruitment strategy was an efficient way to improve arterial oxygenation.

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It is well established that general anaesthesia in the adult patient may be associated with arterial hypoxaemia.[1] In 1963, Bendixen, Hedley-Whyte and Laver suggested that intraoperative atelectasis was the major cause of alterations in gas exchange.[2] Others have shown atelectasis within 5 min of the onset of anaesthesia which did not increase further.[3] The amount of atelectasis on CT scan correlated with the amount of intrapulmonary shunt and it was concluded that alveolar collapse and ventilation/perfusion mismatching were the main reasons for the poor gas exchange during general anaesthesia.[4–6] These findings were supported by lung histology in anaesthetized sheep.[7]

Lachmann suggested a strategy to open atelectatic lungs by sufficient inspiratory pressures and keeping them open by sufficient PEEP.[8] He suggested that a treatment that combined an initial pressure increase beyond the opening pressures of collapsed alveoli with enough PEEP to stabilize the newly opened units would reduce atelectasis and improve lung compliance. When the lung available for gas exchange is increased, abnormalities of arterial oxygenation would be seen less frequently.[9] Gunnarsson and colleagues studied how age affected the formation of atelectasis and gas exchange impairment during general anaesthesia and found that young patients were more prone to atelectasis and intrapulmonary shunting than older patients. Provided they were measurable, the effects of our 'alveolar recruitment strategy' should then be detectable even in an older patient population with a known low risk for the formation of atelectasis but pronounced ventilation/perfusion mismatching.[10]

In this low-risk population, a good response to the recruitment manoeuvre would suggest that further investigations of the postoperative benefits and risks of the manoeuvre are warranted, especially for patients with lungs that are particularly prone to collapse such as during upper abdominal, laparoscopic or thoracic surgery.

We have tested the impact of a simple 'alveolar recruitment strategy' on arterial oxygenation and lung mechanics of patients undergoing general anaesthesia for more than 2 h. Additionally, the frequency and extent of haemodynamic changes and other complications were monitored.

Patients and methods

The study was conducted at the Hospital Privado de Comunidad in Mar del Plata, Argentina, after obtaining approval from the Local Ethics Committee and written informed consent from each patient. Preliminary investigations indicated that 30 patients would be required. Patients older than 60 yr of age, classified as ASA II-III, were randomized prospectively to one of three groups of 10 by opening sealed envelopes. We recruited patients undergoing elective operations not expected to directly affect the thorax or the position of the diaphragm. Patients undergoing thoracic, upper abdominal, spinal and laparoscopic surgery were excluded. All patients had to be supine during surgery and the expected duration of general anaesthesia had to be at least 2 h.

No premedication was given. All patients were preoxygenated with pure oxygen for 3 min; thereafter, anaesthesia and neuromuscular block were induced by thiopental (thiopentone) 3 mg kg^{-1}, fentanyl 3 μg kg^{-1}, vecuronium 0.08 mg kg^{-1} and isoflurane concentrations up to 1 MAC. After intubation of the trachea, anaesthesia was maintained with isoflurane concentrations of 0.5 and 1 MAC combined with bolus doses of fentanyl 1 μg kg^{-1} as needed. Neuromuscular block was monitored continuously. Approximately 15% of the initial dose of vecuronium was administered if train-of-four (TOF) stimulation showed the third response.

After intubation, the lungs were ventilated with 40% oxygen in nitrogen using a Servo 900 B ventilator (Siemens-Elema, Solna, Sweden) in volume controlled mode at a tidal volume of 7–9 ml kg^{-1} and a ventilatory frequency of 10–12 bpm. The respiratory cycle was divided into 25% active inspiration with a constant flow, 10% pause and 65% expiration. Initially, no PEEP was used. Minute ventilation was adjusted to maintain end-tidal carbon dioxide partial pressure within the range 4.0–4.7 kPa. After reaching a new steady state, the ventilator adjustments were confirmed by arterial blood-gas analysis.

After the start of surgery, the lungs were ventilated using the ventilator settings as described above for an initial control period of 30 min. Before patients were allocated randomly to one of the following three groups, arterial blood-gas measurements were obtained and baseline data recorded: in group ZEEP, patients continued with the same ventilator settings as during the control period (no PEEP was given); in group PEEP, after randomization, PEEP 5 cm H_2O was added to the treatment regimen; in the strategy group, alveolar recruitment was achieved by applying steps 1–7 (below) sequentially. Figure 1 shows a schematic representation of the recruitment plan.

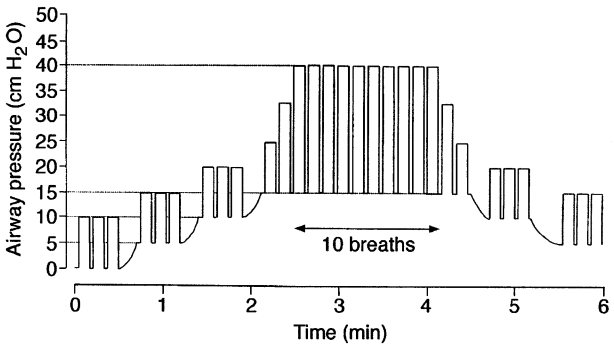

Fig 1 Schematic representation of the 'alveolar recruitment strategy': PEEP is incremented in three steps of 5 cm H_2O each. The vertical rectangles represent tidal breathing with a tidal volume of 7–9 mg/kg body weight at a ventilatory frequency of 8 bpm. At a PEEP of 15 cm H_2O, tidal volumes are increased until a maximum tidal volume of 18 ml kg^{-1} or a peak airway pressure of 40 cm H_2O is reached. These settings are applied for 10 breaths. Thereafter, tidal volumes are reduced to previous values. Finally, PEEP is set to a level of 5 cm H_2O in two steps.

(1) For safety reasons, the working pressure of the ventilator was limited to 40 cm H_2O.

(2) PEEP was increased in steps of 5 cm H_2O up to a maximum of 15 cm H_2O to obtain information on the haemodynamic state of the individual patient. If a patient's mean arterial pressure or heart rate changed by more than 20% compared with baseline, the intervention was stopped and normal saline 500 ml was given before the next recruitment attempt.

(3) Ventilatory frequency was reduced to 8 bpm.

(4) Pause time was increased to 20%.

(5) Tidal volume was increased until either a tidal volume of 18 ml kg^{-1} or a peak inspiratory pressure of 40 cm H_2O was reached. These latest settings were maintained for 10 breaths.

(6) Tidal volume was then reduced to baseline values.

(7) PEEP was decreased twice to obtain PEEP 5 cm H_2O. The final ventilator settings were the same as in the PEEP group.

Monitoring

A Capnomac Ultima (Datex Instruments, Corp., Helsinki, Finland) measured and displayed concentrations of carbon dioxide and oxygen in the ventilation gases. The device has a flow and pressure transducer which measured peak airway pressure, PEEP, expired tidal volume and minute ventilation at the distal end of the tracheal tube. Auto-PEEP was measured by clamping the expiratory limb of the ventilator breathing system just before the start of the next inspiration. To obtain reproducible conditions during measurement of lung mechanics that were independent

of resistance and auto-PEEP, ventilatory frequency was temporarily reduced to 7 bpm and the pause was prolonged to 20% to obtain an inspiratory pause of 1.7 s. Quasi-static compliance was then calculated by dividing expiratory tidal volume by the pressure difference between the plateau and total end-expiratory pressure (set-PEEP+auto-PEEP).

Systolic and diastolic arterial pressures were measured non-invasively by a Cardiocap II (Datex Instruments, Corp., Helsinki, Finland) and displayed together with Sp_{O_2} on the monitor. Blood-gas samples were obtained via an 18-gauge radial artery cannula, inserted before induction of general anaesthesia under local anaesthesia.

Patients who received the recruitment manoeuvre had a portable chest x-ray within 12–24 h after surgery. All patients were followed until discharge from hospital for possible complications.

Blood-gas analysis

After the initial 30-min control period (baseline), and at 40, 80 and 120 min, arterial blood samples were analysed for Pa_{O_2},Sp_{O_2}, Pa_{CO_2} and pHa by a blood-gas analyser (ABL 510; Radiometer, Copenhagen, Denmark). Samples were processed within 5 min and were corrected for body temperature. The investigators did not see the results of the blood-gas analysis until the end of the study.

Statistical analysis

Descriptive statistics, intra- and inter-group analysis with repeated measures ANOVA were performed using INSTAT 2.0 (GraphPad Software, San Diego, CA, USA). In addition, the mixed model ANOVA of the SAS statistical package was used for oxygenation and compliance data (SAS Institute Inc., Cary, NC, USA). $P<0.05$ was taken as significant.

Results

Baseline characteristics

Between October 1996 and June 1997, 30 patients were allocated randomly to one of three treatment blocks. One patient in the recruitment group did not complete the 120-min study period but data up to 80 min were included in the analysis. Table 1 gives the baseline characteristics and type of surgery for the study population.

Table 2 shows the data obtained during the recruitment strategy. During recruitment, no cardiovascular changes were noted that required interruption of the procedure. Table 3 shows the effects of the treatments on Pa_{O_2} and lung compliance.

Lung mechanics

Baseline plateau pressures did not differ between groups. The recruitment and PEEP groups showed a significant difference in plateau and end-expiratory pressures compared with the ZEEP group; there were no differences between the recruitment and PEEP groups at 40, 80 or 120 min.

At 40, 80 and 120 min, compliance of the recruited lungs was different from baseline, but no such effect was seen after application of PEEP 5 cm H_2O without prior recruitment. There was no time-dependent increase

Table 1 Patient baseline characteristics and type of surgery. Age (yr), BMI= body mass index (kg m^{-2}). *Anterior approach

Group	Age	BMI	Sex	ASA	Surgery
Strategy	80	21	F	III	Iliac-femoral bypass
	62	30	M	II	Ureterectomy
	76	24	F	III	Left hemicolectomy
	85	24	F	III	Left hemicolectomy
	65	22	F	II	Explorative laparotomy
	64	22	F	II	Cervical discectomy*
	62	29	F	II	Cervical discectomy*
	68	29	F	II	Left hemicolectomy
	60	26	M	II	Left hemicolectomy
	64	26	M	III	Kidney transplant
Mean	69	25	3M–7F	4/III–6/II	
SD	8.6	3.2			
PEEP	81	26	F	III	Left hemicolectomy
	67	25	F	III	Left hemicolectomy
	60	21	M	II	Right hemicolectomy
	75	23	M	II	Left hemicolectomy
	71	22	F	II	Left hemicolectomy
	60	30	M	II	Cervical discectomy*
	68	27	M	III	Cerebral tumour excision
	73	28	M	III	Left hemicolectomy
	71	27	F	II	Cervical discectomy*
	81	21	M	III	Total colectomy
Mean	70.7	25.0	6M–4F	5/III–5/II	
SD	7.3	3.1			
ZEEP	78	26	M	III	Cervical discectomy*
	78	26	F	II	Ceratoplasty
	61	25	F	III	Clip cerebral aneurysm
	77	21	F	II	Retinopexia
	60	23	M	II	Clip cerebral aneurysm
	77	24	F	II	Hartman operation
	74	23	F	II	Right hemicolectomy
	75	25	M	III	Segmental colon resection
	80	21	F	III	Hartman operation
	63	21	F	II	Excision cerebral tumour
Mean	72.3	23.5	3M–7F	4/III–6/II	
SD	7.7	2.0			

Table 2 Data obtained during the 'alveolar recruitment strategy' (mean (SD))

Variable	
Peak pressure (cm H_2O)	39.8 (0.8)
Plateau pressure (cm H_2O)	35.4 (0.7)
PEEP (cm H_2O)	15.6 (1.6)
Tidal volume (ml)	1064 (210)
Compliance (ml cm H_2O^{-1})	65.1 (26.8)
Ventilatory frequency (bpm)	8.2 (0.4)
Sp_{O_2} (%)	98.9 (0.6)
End-tidal CO_2 (kPa)	3.74 (0.38)
Heart rate (beat min^{-1})	75.3 (12.5)
Systolic arterial pressure (mm Hg)	112 (14)
Diastolic arterial pressure diastol (mm Hg)	68 (16)

Table 3 Median, minimum and maximum values for Pa_{O_2} and compliance. *Significant difference from baseline at $P<0.05$ using a mixed model ANOVA. Dependent variables: Pa_{O_2} and compliance at times 40, 80 and 120 min. Independent variables: baseline data as covariates. Within-patient factor: time (three levels); between-patient factor: group (three levels). We did not make any assumption about the structure of the within-patient (co)-variance matrix of the residuals

Variable	Time	ZEEP	PEEP	Recruitment
Pa_{O_2} (kPa)	Basal	18.7 (12.8–26.3)	13.0 (10.2–20.6)	20.4 (10.4–25.3)
	40 min	18.5 (15.0–29.1)	16.2 (12.2–21.4)*	24.4 (13.3–35.2)*
	80 min	18.9 (14.6–27.6)	19.3 (10.5–23.9)	25.5 (18.0–31.1)
	120 min	17.1 (14.9–26.2)	20.3 (11.4–24.5)	25.4 (18.0–36.8)
Compliance (cm H_2O)	Basal	46.5 (34–76)	47.0 (35–68)	47.5 (28–55)
	40 min	44.5 (26–70)	48.0 (37–66)	50.5 (29–74)*
	80 min	44.0 (33–64)	47.0 (31–67)	57.0 (38–75)
	120 min	43.0 (34–72)	45.5 (36–68)	62.0 (29–68)

in compliance in the ZEEP group. No inter-group differences were seen.

Blood-gas analysis

Recruitment increased arterial oxygenation compared with baseline. This persistent increase in Pa_{O_2} was also significantly different from the two other groups. Applying PEEP 5 cm H_2O after baseline measurements improved Pa_{O_2} for the rest of the study but there were no inter-group differences in oxygenation between groups PEEP and ZEEP. Pa_{CO_2} and pHa remained in the normal range and showed no significant differences between groups or within groups over time. Pa_{O_2}–end-tidal carbon dioxide was always lower in recruited lungs but was significantly different (0.27 (0.35) *vs* 0.76 (0.31) kPa) ($P<0.01$) between the strategy group and ZEEP group only at 80 min.

Monitoring

Sp_{O_2}, end-tidal carbon dioxide concentration, heart rate, systolic and diastolic arterial pressures were within the normal range during the study. No complications occurred in any patient.

Discussion

The ‘alveolar recruitment strategy’ increased arterial oxygenation during general anaesthesia. Treatment with PEEP 5 cm H_2O alone, however, did not have the same effect on oxygenation. The increase in arterial oxygenation after the recruitment manoeuvre suggests a reversal of anaesthesia-induced atelectatic and the ventilation/perfusion inhomogeneity. This finding is compatible with the results of Hedenstierna and colleagues.[3–6 10–14]

Mechanisms of impaired oxygenation may also include collapse of alveoli, displacement of blood from the thorax to the abdomen, reduction in thoracic diameter and displacement and dysfunction of the diaphragm.[15 16] Methods to restore normal FRC and various re-expansion manoeuvres have been suggested. In 1978, Nunn and colleagues tested the detection and reversal of pulmonary absorption collapse in six healthy volunteers.[17] They found a correlation between the reduction in FRC with Pa_{O_2} and densities on chest x-ray. All of these changes were abolished by deep spontaneous inspirations. Rothen and colleagues reported experimental and clinical studies on the prevention and treatment of atelectasis.[13 14 18 19] They demonstrated in volunteers that peak inspiratory pressures of at least 40 cm H_2O were needed to fully reverse anaesthesia-induced collapse of healthy lungs.[13 14]

Tokics and colleagues used CT and inert gases to investigate 13 patients undergoing general anaesthesia.[4] The subjects were examined while breathing spontaneously before and after induction of anaesthesia. After intubation of the trachea, ZEEP or PEEP 10 cm H_2O was applied. The authors found, in contrast with our results, that PEEP 10 cm H_2O reversed the lung densities on the CT scan but showed no effect on arterial oxygenation.[4] PEEP altered the relation between intrapulmonary shunt and atelectasis measured on the CT, and the authors suggested that the increased intra-thoracic pressures caused redistribution of blood flow towards the dependent atelectatic and shunting lung zones.[4] These results confirm earlier x-ray studies by Froese and Bryan, who found a PEEP-induced asymmetric displacement of the non-dependent diaphragm.[20]

To find a treatment for anaesthesia-induced atelectasis it may be useful to look at studies of mechanical ventilation performed in the diseased lung. Studies in the adult respiratory distress syndrome showed that collapsed alveoli can be opened even in these collapse-prone lungs.[21–25] These results encouraged our group to use the same treatment principles in healthy lungs with known atelectasis.[8 9] Therefore, an active re-expansion manoeuvre was combined with stabilization of the newly recruited alveoli by PEEP. After this intervention, arterial oxygenation increased immediately and remained high. During the 2-h study, the PEEP group showed a significant change in oxygenation which was, however, less pronounced than in the recruited group. Whether a longer investigation period would have revealed a significant increase is not known. These findings indicate that pressures beyond the opening pressure of collapsed alveoli are necessary to overcome the anaesthesia-induced collapse,[13] and that PEEP 5 cm H_2O or more is required to prevent the newly recruited alveoli from collapsing.[9 14]

In our small study group, the low baseline oxygenation in the PEEP group compared with the strategy and ZEEP groups was most likely a result of chance alone, especially as no such initial difference between groups was found in the corresponding compliance values. It is not clear how this difference in Pa_{O_2} may have affected our results.

Although we intentionally applied 'high' airway pressures, no patient showed evidence of barotrauma on x-rays obtained after surgery and there were no pulmonary complications before hospital discharge. There are recommendations that plateau pressures greater than 35 cm H_2O should be avoided and that alveoli should be stabilized with sufficient levels of PEEP.[26] In our study, mean plateau pressure during the intervention was 35.4 (0.7) cm H_2O, that is at the limit proposed by the consensus conference on mechanical ventilation. In addition, we only applied increased inspiratory pressures for a total of 33.7 s. Our study regimen included application of PEEP 15 cm H_2O during the recruitment process to reduce pressure amplitude. Tidal volumes did not exceed an average of 14.6 ml/kg body weight. In this way, we reduced large swings in alveolar surface area and shear forces that could damage the pulmonary surfactant system and alveolar structure.[27–29]

The recruitment manoeuvre can be performed with any conventional anaesthesia ventilator. For safety reasons, in our study the working pressure of the volume control ventilator was set to 40 cm H_2O. This limited the maximum plateau and thus the effective recruiting pressure. Perhaps the oxygenation obtained in our study could have been greater had a recruitment pressure of 40 cm H_2O or more been applied.[13] Ventilation by a pressure-limited mode, suggested by Lachmann and colleagues, could have filled opening alveoli more effectively.[22]

In summary, the 'alveolar recruitment strategy' is an efficient intervention to correct abnormalities in gas exchange during general anaesthesia. This recruitment manoeuvre was easy to perform and showed no complications in this small number of patients with healthy lungs. Further studies are needed to address the postoperative benefits and possible side effects of our recruitment manoeuvre.

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