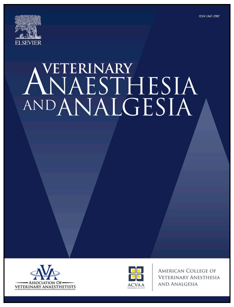

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An alveolar recruiting maneuver followed by positive end-expiratory pressure improves lung function in healthy dogs undergoing laparoscopy

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Abstract

Objective To evaluate the effects of an alveolar recruiting maneuver (ARM) followed by 5 cmH_2O positive end-expiratory pressure (PEEP) in dogs undergoing laparoscopy.

Study design Prospective, randomized clinical study.

Animals Twenty dogs undergoing laparoscopic ovariectomy.

Methods Dogs were sedated with acepromazine and methadone intramuscularly, anesthesia was induced with propofol intravenously and maintained with inhaled isoflurane. The following baseline ventilatory setting (BVS) were administered: tidal volume of 12 mL kg^{-1}, inspiratory-to-expiratory ratio of 1:2, inspiratory pause 25% of inspiratory time, no PEEP and a respiratory rate to maintain end-tidal carbon dioxide tension between 5.3 and 7.3 kPa. Ten minutes after the pneumoperitoneum, 10 patients (RM) underwent a sustained inflation ARM followed by the BVS plus 5 cmH_2O PEEP, while 10 patients (NO-RM) were left with the BVS throughout the entire procedure. Gas exchange and respiratory system mechanics were evaluated before the pneumoperitoneum (PPpre), before the ARM (PP10), 30 minutes later (PP30) and 20 minutes after pneumoperitoneum discontinuation (PPpost20). Data were analyzed with the ANOVA test ($p < 0.05$).

Results The Fshunt at PP30 and PPpost20 was lower ($p < 0.001$) in the RM (2.3 ± 2.2 and 4.7 ± 3.7 %) than in the NO-RM (5.2 ± 2.1 and 11.1 ± 5.2 %), and PaO_2 at PP30 and PPpost20 was higher ($p < 0.001$) in the RM (67.3 ± 4.2 and 60.1 ± 9.4 kPa) than in the NO-RM (50.2 ± 7.4 and 45.5 ± 11.1 kPa). Static compliance of the respiratory system at PP30 and PPpost20 was greater ($p < 0.001$) in the RM (2.4 ± 0.2 and 2.1 ± 0.4 mL cmH_2O^{-1} kg^{-1}) than in the NO-RM (0.9 ± 0.4 and 1.2 ± 0.2 mL cmH_2O^{-1} kg^{-1}).

Conclusions and clinical relevance In dogs undergoing laparoscopy, an ARM followed by 5 cmH_2O PEEP improves gas exchange and respiratory system mechanics.

Keywords dog, laparoscopy, oxygenation, alveolar recruitment

Introduction

Laparoscopic and laparoscopic-assisted procedures are becoming increasingly available to veterinary patients because they cause less tissue trauma, are associated with reduced postoperative pain and rates of surgical site infection, and result in faster postoperative recovery compared with traditional open surgery (Devitt et al. 2005; Mayhew et al. 2012; Milovancev & Townsend 2015). Laparoscopy requires the formation of a working area within the peritoneal cavity, which is commonly achieved by the insufflation of carbon dioxide (CO_2). However, the creation of CO_2 pneumoperitoneum (PP) causes significant changes in respiratory and cardiovascular function (Duke et al. 1996; Bailey & Pablo 1999; Carraretto et al. 2005; Park & Okano 2015). The most critical events induced by CO_2-PP are an increase in intra-abdominal pressure (IAP) and systemic absorption of CO_2 at the abdominal level. An increase in arterial partial pressure of carbon dioxide ($PaCO_2$) and a reduction in pH are typical acid-base disturbances associated with the systemic absorption of CO_2 (Fukushima et al. 2011). Guidelines in human medicine and standard of care in veterinary medicine indicate that a safe value for IAP is $\leq$ 15 mmHg (Neudecker et al. 2002; Tams 2011; Dorn et al. 2017). Most studies investigating the cardiovascular changes associated with laparoscopic surgery in people and dogs report an increase in systemic vascular resistance (SVR), mean arterial blood pressure (MAP) and myocardial filling pressures, accompanied by a fall in cardiac index (CI), with little change in heart rate (HR) (Duke et al. 1996; O'Malley & Cunningham 2001; Carraretto et al. 2005).

The increase in IAP induces a 30–50% decrease in thoraco-pulmonary compliance and general impairment of lung function due to the cranial shift of the diaphragm, which reduces functional residual capacity and promotes the formation of pulmonary atelectasis and a ventilation/perfusion mismatch in the most dependent areas of the lung as a result of compression of the pulmonary parenchyma (Andersson et al. 2005; Carraretto et al. 2005; Nguyen & Wolfe 2005; Strang et al. 2010). Thus, in patients undergoing laparoscopy, the increased IAP is an additional factor promoting the formation of atelectasis, in addition to the regular effects of general anesthesia

(Hedenstierna 2003; Staffieri et al. 2007). Perioperative atelectasis affects gas exchange and is accepted as a major cause for the development of postoperative hypoxia (Tusman et al. 2012; Staffieri et al. 2014).

Positive pressure ventilation is highly recommended in animals undergoing laparoscopy in order to cope with the increased work of breathing related to the PP and to optimize lung ventilation for the increased elimination of CO_2 (Bailey & Pablo 1999; Nguyen & Wolfe 2005). Alveolar recruitment consists of the reexpansion of collapsed alveolar units, and recruitment strategies are aimed at increasing the pressure distending the lung (transpulmonary pressure, P_L) to an extent that the latter overcomes the opening pressure of the alveoli, thus causing their reexpansion (Tusman & Bohm 2010). Positive end-expiratory pressure (PEEP) is an essential component in the management of alveolar collapse during anesthesia, its main physiological mechanisms being an increase in functional residual capacity and P_L, thus promoting alveolar recruitment (Slutsky & Hudson 2006; Acosta et al. 2007). Moreover, PEEP has a unique role in stabilizing the unstable alveolar units at end expiration, preventing the cycling collapse of the alveoli (de-recruitment) (Tusman & Bohm 2010). During PP, the cranial shift of the diaphragm and the elevated IAP further increase the compressing forces on the pulmonary parenchyma, developing collapsed alveolar units with elevated opening pressures. It is for this reason that such a condition needs higher distending pressures, and the application of standard levels of PEEP may not be sufficient to overcome the alveoli’s opening pressures (Maracaja-Neto et al. 2009).

An alveolar recruiting maneuver (ARM) consists of the application of high airway pressure for a limited period to completely distend the lung parenchyma. A “vital capacity” ARM consists of insufflating the lungs to an airway pressure of 30 - 40 cmH_2O for 20-40 seconds in order to re-expand the entire lung (Staffieri et al. 2010). In standard laparotomic procedures in dogs, an ARM followed by 5 cmH_2O PEEP was adequate to resolve anesthesia-induced pulmonary atelectasis as indicated by computed tomography studies (De Monte et al. 2013)

The aim of this study was to evaluate the effects of a vital capacity ARM followed by the application of 5 cmH_2O PEEP in dogs undergoing laparoscopy. The hypothesis was that the recruiting strategy would improve lung function compared with a traditional ventilatory protocol. To test our hypothesis gas exchange, respiratory system mechanics and hemodynamics were monitored and compared at predetermined times during the procedure.

Materials and methods

The study was approved by the Ethical Committee for Clinical Study in Animal Patients of the Department Emergency and Organ Transplantation of the University of Bari (n. 03/2016). On the basis of the preliminary data obtained after the first eight cases (four for each group), a power calculation was performed for differences in arterial partial pressure of oxygen (PaO_2) at 30 minutes after the beginning of PP (PP30). We performed the power calculation for a two-tailed t test with power of 0.95, an alpha error of 0.05 and an effect size of 1.66, using freely available software (G*Power Version 3.0.10; University of Düsseldorf, Germany) (Faul et al. 2009). The results of this analysis suggested that a minimum of nine dogs per group would be sufficient to detect significant differences between groups.

Animals

Twenty mixed-breed, adult female dogs were selected for laparoscopic ovariectomy and included in the study after the owner provided informed written consent. All animals were clinically healthy based on the physical examination, complete blood count and serum biochemical analyses. Any dog presenting with systemic disease, cardiac arrhythmias, pregnancy or extreme aggression or one that was excessively geriatric, obese or debilitated was excluded from the study. The dogs were admitted 16 hours before surgery and fasted during the night with free water access until premedication.

Anesthetic and surgical procedure

The anesthetic protocol comprised premedication with intramuscular (IM) administration of 10 μg kg^{-1} acepromazine (Prequillan; Fatro, Italy; 10 mg mL^{-1}) followed after 15 minutes by 0.3 mg kg^{-1} methadone (Semfortan; Dechra, Italy; 10 mg mL^{-1}) IM. After an adequate level of sedation was achieved, a cephalic vein was cannulated for the intravenous (IV) administration of drugs and fluids. General anesthesia was induced with propofol (5 mg kg^{-1}) IV and maintained with inhaled isoflurane and pure oxygen administered through a rebreathing system. When an adequate depth of anesthesia was achieved, dogs were positioned in dorsal recumbence with a 15–20° head-up tilt (anti-Trendelenburg). All dogs were mechanically ventilated during the entire procedure in a volume-controlled mode (Siemens Maquet Servo-I Ventilator) with a baseline ventilatory setting (BVS) consisting of a tidal volume (V_T) of 12 mL kg^{-1}, an inspiratory-to-expiratory ratio of 1:2, an inspiratory pause of 25% of inspiratory time and a PEEP of 0 cmH_2O. The respiratory rate (f_R breaths $minute^{-1}$) was adjusted on the basis of the end-tidal carbon dioxide tension ($P_{E'}CO_2$) level, which was maintained between 40 and 55 mmHg (5.3 and 7.3 kPa). An arterial catheter (20–22 gauge) was placed in one of the palmar arteries for the hemodynamic monitoring and collection of the arterial blood samples. During the entire procedure, the following physiological parameters were monitored and recorded every 5 minutes: HR (beats $minute^{-1}$), invasive systolic arterial pressure (mmHg), diastolic arterial pressure (mmHg), MAP (mmHg), f_R, $P_{E'}CO_2$, peripheral capillary oxygen hemoglobin saturation (%), peak airway pressure (P_{peak}, cmH_2O) and end-tidal concentration of isoflurane (%).

The PP was created by insufflation of CO_2 into the abdominal cavity via a Veress needle with a common CO_2 insufflator (Endoflator, Karl-Storz, Germany) until the IAP reached 10 mmHg. At the end of surgery (ovariectomy), PP was discontinued, the abdominal wall was sutured and dogs were recovered from general anesthesia by standard care. Fluid therapy and heating support were discontinued when dogs were fully awake and the rectal temperature was above 37.5 °C, respectively. The duration of surgery (from skin incision to last skin suture) and of the PP were recorded in all cases.

Study protocol

Ten minutes after induction of PP, dogs were randomly divided into two groups by using computer-generated random numbers (Microsoft Excel). Ten animals (group RM) underwent a sustained inflation ARM: lungs were inflated to an airway pressure of 40 cm H_2O for 20 seconds. To perform this recruitment maneuver, the ventilator was temporarily switched to a continuous positive airway pressure mode that applied a pressure of 40 cm H_2O for 20 seconds to the dog's respiratory system (Staffieri et al. 2010). Thereafter, the BVS was resumed with the addition of 5 cmH_2O PEEP and maintained till the end of anesthesia. The remaining 10 dogs (group NO-RM) were ventilated with the BVS throughout the entire procedure. Gas exchange, respiratory system mechanics and hemodynamics were evaluated 5 minutes before the induction of PP (PPpre), 10 (PP10) and 30 (PP30) minutes after the beginning of PP, and 20 minutes after its discontinuation (PPpost20). At PP10, measurements were performed immediately prior to the ARM in the RM group, with the dogs still ventilated with the BVS.

Gas exchange assessment

For gas exchange assessment, an arterial blood sample (1 mL) was collected from the arterial line before measurement of respiratory mechanics to avoid any interference of the latter procedures with the blood gases determination. Blood was immediately analyzed. Arterial blood pH (pH), PaO_2 and $PaCO_2$ were measured and corrected for the body temperature of the dog at the time of sampling. Arterial blood O_2 saturation (SaO_2, %) was calculated by the analyzer. The PaO_2:FIO_2 ratio was calculated as an index of arterial blood oxygenation.

The estimated intrapulmonary blood shunt percentage (Fshunt) was calculated as follows (Araos et al. 2012):

$$Fshunt = ([Cc'O_2 - CaO_2]/[Cc'O_2 - CaO_2 + 3.5\ mL\ dL^{-1}]) \times 100$$

where $Cc'O_2$ is the pulmonary end-capillary oxygen content, CaO_2 is the arterial oxygen content, and 3.5 mL dL^{-1} is an approximate fixed value of the arterial-to-mixed venous oxygen content difference. $Cc'O_2$ and CaO_2 were calculated as follows:

$$Cc'O_2 = Hb \times 1.31 \times Sc'O_2 + 0.0031 \times Pc'O_2$$

$$CaO_2 = Hb \times 1.31 \times SaO_2 + 0.003 \times PaO_2$$

where Hb is the hemoglobin concentration (g dL^{-1}), 1.31 is the oxygen-carrying capacity of hemoglobin (mL g^{-1}), $Sc'O_2$ is the pulmonary end-capillary oxygen saturation, 0.003 is the solubility coefficient of oxygen in dog plasma (Haskins et al. 2005) and $Pc'O_2$ is the pulmonary end-capillary partial pressure of oxygen. The $Pc'O_2$ was assumed to be equal to PAO_2. For $PAO_2 >$ 100 mmHg (13.3 kPa), $Pc'O_2$ was assumed to be 100%; for $PAO_2 \leq$ 100 mmHg (13.3 kPa), $Pc'O_2$ was calculated from the actual PAO_2 via the same method. The difference between the arterial and the end-tidal partial pressure of CO_2 [$P(a\text{-}\ E')CO_2$] was also calculated (Strang et al. 2009).

Evaluation of respiratory system mechanics

For each dog, gas flow was measured with a heated pneumotachograph connected to a differential pressure transducer placed between the Y-piece of the ventilator circuit and the endotracheal tube. The pneumotachogram was linear over the experimental range of gas flows. Tidal volume and minute ventilation ($\dot{V}\text{E}$, L $minute^{-1}$ kg^{-1}) were obtained by numerical integration of the flow signal. Values of the airways pressures (cmH_2O) were measured proximally to the endotracheal tube with a pressure transducer. To estimate the static mechanical properties of the respiratory system, we performed an end-inspiration and an end-expiration automatic airway occlusion (3- to 5-second duration each) at each study time via operation of the appropriate control of the ventilator that closes the inspiratory and the expiratory branches of the circuit system at the end of an inspiration and expiration, respectively (Gottfried et al. 1985).

The level of PEEP applied to the respiratory system was measured as the airway plateau pressure during the end-expiratory occlusion. The static compliance of the respiratory system, $Cst,_{RS}$ (adjusted for the dog's body weight), was calculated as follows:

$$Cst,_{RS}\ (\text{mL cmH}_2\text{O}^{-1}\ \text{kg}^{-1}) = (V_T/[P_{plat} - \text{PEEP}]) \div \text{body weight}$$

where P_{plat} (cmH_2O) is the value of the airway pressure during the 4-second end-inspiratory occlusion.

For further data analysis, values of the aforementioned variables were displayed and collected on a personal computer through a 12-bit analog-to-digital converter board at a sample rate of 200 Hz. The pneumotachograph and the transducers used to measure flow and pressures underwent two-point calibration before the beginning of each experiment.

Hemodynamic evaluation

The arterial catheter (20–22 gauge) was connected to a transducer with a dedicated saline-filled line and zeroed at the right atrial level. A square wave test was performed at each time point before data collection. Cardiac output (CO, L minute^{-1}), SVR (dynes × seconds cm^{-5}), MAP and HR were evaluated with a pressure recording analytical method (PRAM, Most Care; Vytech, Italy) at each study time. The PRAM is a pulse contour method, which estimates stroke volume and other hemodynamic parameters from the analysis of the arterial pulse waveform (Romagnoli et al. 2009) and it has been recently validated in dogs (Briganti et al. 2018). The CI in L minute^{-1} m^{-2} was calculated by using the following formula: CI = CO/BSA, where BSA (body surface area) = weight × 0.6667/10 (Muir 2007).

Statistical analysis

Statistical comparisons (MedCalc version 9.2.1.0) of respiratory mechanics, gas exchange and hemodynamic data were performed between and within each group for the four study times. Data were tested for normal distribution by the Shapiro-Wilks test and are presented as mean ± standard deviation (SD). Data analysis was performed by using repeated-measures one-way analysis of variance; if significant, Tukey's test was applied for post hoc comparison between the different experimental conditions. A p value less than 0.05 was considered statistically significant.

Results

The procedure was performed in all animals without any complications. The two groups were similar in terms of body weight (NO-RM = 18.4 ± 7.8 kg; RM = 21.3 ± 7.2 kg), age (NO-RM = 3.2 ± 1.2 years; RM = 3.5 ± 1.2 years), duration of PP (NO-RM = 42.3 ± 5.8 minutes; RM = 46.8 ± 8.3 minutes) and surgery (NO-RM = 52.3 ± 9.2 minutes; RM = 55.4 ± 9.2 minutes).

Gas exchange parameters

The mean ± SD of the gas exchange parameters at each study time are reported in Table 1. PaO_2 and PaO_2:FIO_2 in the NO-RM were similar among study times. The same parameters in the RM group at PP30 ($p < 0.001$) and PPpost20 ($p < 0.05$) were higher than the PPpre value in the RM group and the corresponding values in the NO-RM group ($p < 0.001$) (Figure 1). The PaO_2 and PaO_2:FIO_2 in the RM group were higher at PP30 than at PP10, with a mean percentage variation of +29.2 ± 14.4%, which was larger than the variation in the NO-RM group (-3.7 ± 5.5%). Fshunt in both groups was lower than at PPpre at PP10 and PP30 ($p < 0.001$), as well as at PPpost20 in the RM group ($p < 0.001$). At PP30 and PPpost20, the Fshunt was smaller in the RM ($p < 0.001$) than in the NO-RM group at the same times (Figure 2). Fshunt in the RM group was smaller at PP30 than at PP10, with a mean percentage variation of -68.1 ± 25.4%, which was larger than the variation in the NO-RM group at +2.8 ± 2.6%. In both groups, $PaCO_2$ and $P\text{E}'CO_2$ were higher at PP10 and PP30 than at PPpre ($p < 0.001$). The arterial to end-tidal CO_2 gradient increased significantly ($p < 0.001$) at PP10 in both groups, whereas it was lower at PP30 in the RM group (-50.3 ± 14.3%; $p < 0.001$) than at PP10, and its value remained the same in the NO-RM group ($p < 0.001$) (Figure 3).

Respiratory system mechanics

The mean ± SD of the respiratory system mechanics parameters at each time of the study are reported in Table 2. The P_{peak} and P_{plat} at PP10 and P20 were higher ($p < 0.05$) than PPpre in both groups, as well as at PPpost20 ($p < 0.05$) in the RM group. At PP30 and PPpost20, P_{peak} was higher in the RM group than in the NO-RM group ($p < 0.05$). Static compliance of the respiratory system was lower than PPpre at PP10 and PP30 in the NO-RM group ($p < 0.01$). In the RM group, Cst,_{RS}, compared with PPpre, was lower at PP10 ($p < 0.01$) and higher at PP30 and PPpost20 ($p < 0.05$). At PP30 and PPpost20, Cst,_{RS} was higher in the RM group than in the NO-RM group (Figure 4). The mean percentage variation of Cst,_{RS} between PP30 and PP10 was greater ($p < 0.001$) in the RM group (+145.2 ± 38.1%) than in the NO-RM group (+21.4 ± 14.6%). The f_{R} and $\dot{\text{V}}\text{E}$ were higher ($p < 0.01$) at PP10 and PP30 than at PPpre in both groups.

Hemodynamic parameters

The mean ± SD of the hemodynamic parameters at each study time are reported in Table 3. Heart rate, MAP, CI and SVR did not show significant differences between the two groups at any study time (Table 1). Heart rate increased significantly at PP10 compared with PPpre in the NO-RM group. Cardiac index was lower at PP10 compared with PPpre in both groups.

Discussion

The main findings of this study are that the derangement of respiratory function induced by PP in healthy dogs under general anesthesia can be reversed with a vital capacity ARM followed by the application of 5 cmH_2O PEEP. The lung recruitment strategy tested in this study improved oxygenation and respiratory system mechanics compared with those of the control group. Our results confirm that PP in dogs significantly impairs respiratory function, with an average 34% reduction of Cst,_{RS} and increased airway pressures (P_{peak} + 32%; P_{plat} +41%), PaCO_2 (+29%) and

P(a- E´)CO_2 (+29%) 10 minutes after the induction of PP in the entire study population, similar to what has been found in human patients (Duke et al. 1996; Cinnella et al. 2013). Oxygenation seemed to be affected in the opposite direction by PP, as indicated by the slight improvement in PaO_2:FIO_2 (+7%) and significant reduction in FShunt (-34%) at PP10 compared with those at PPpre. This seeming paradox has already been documented and investigated in the literature on animal models and human patients: despite an increase in the formation of atelectasis during PP (Andersson et al. 2005), venous admixture may not increase and oxygenation may not decrease (Odeberg & Sollevi 1995; Andersson et al. 2002). In attempting to understand this mechanism, Strang et al. (Strang et al. 2010) demonstrated that improved gas exchange and oxygenation is caused by the redistribution of blood flow away from collapsed lung tissue during PP, resulting in a better ventilation/perfusion match. A likely, but not yet proven, explanation is enhanced hypoxic pulmonary vasoconstriction, possibly mediated via increased $PaCO_2$ (Loeppky et al. 1992; Ho et al. 1995). During CO_2-PP, PaO_2:FIO_2 and shunt do not correlate with the amount of lung collapse, precluding arterial oxygenation as a predictor of the amount of atelectasis. On the other hand, P(a-E')CO_2 has been shown to have a strong correlation ($r^2 = 0.92$) with lung collapse, making this parameter an alternative for the estimation of atelectasis during PP (Strang et al. 2009). In our dogs, P(a- E´)CO_2 increased similarly in both groups at PP10, indicating an increase in lung collapse (Figure 3). At PP30, the same parameter diverged between the two groups, with a substantial reduction to levels similar to PPpre in RM, most likely as an effect of the recruiting strategy applied in these animals. The increase in PaO_2:FIO_2, PaO_2 and $Cst,_{RS}$ and the reduction of FShunt at PP30 compared with that at PP10 also confirmed the effectiveness of the ARM strategy in promoting alveolar recruitment and thus improving oxygenation. The fact that the same parameters in NO-RM at PP30 stayed at the same levels as PP10 confirms that the improvement in lung function observed in the RM group was an effect of the ARM strategy, excluding any time influence. To our knowledge, this is the first study that used P(a- E´)CO_2 in a clinical setting and indirectly proved the usefulness of this parameter in monitoring lung collapse and recruitment during CO_2-PP.

Several recruitment strategies have been evaluated in human patients during laparoscopy with variable results. The application of a fixed PEEP value (5–10 cmH_2O) has been proven to have limited or null effects on respiratory system mechanics and oxygenation (Meininger et al. 2005; Almarakbi et al. 2009). A single ARM produced a transient improvement (10–20 minutes) in oxygenation and respiratory system mechanics. These effects, similar to those of our study, lasted longer when low levels of PEEP were applied after the ARM (Almarakbi et al. 2009; Cinnella et al. 2013). On the basis of the open lung concept, a recruiting strategy should provide a temporary elevated P_L to open the collapsed alveoli, which thereafter can be kept open by lower pressure levels from the application of PEEP (Tusman & Bohm 2010). The recruitment strategy used in our dogs was demonstrated to be effective in promoting lung recruitment and in improving oxygenation and respiratory system mechanics in dogs undergoing laparoscopy. Cinnella et al. (Cinnella et al. 2013) demonstrated, in human patients, that the strategy applied in this study recruits the collapsed lung units and keeps them open by increasing P_L. Moreover, they were able to prove that such a recruitment strategy significantly improved chest wall mechanics. Our study was limited to the monitoring of the cardiovascular and respiratory parameters up to 30 minutes after the recruitment maneuver during PP; thus, we cannot guarantee that, for longer laparoscopic procedures, the beneficial effects of the recruitment strategy would persist. Almarakbi et al. (Almarakbi et al. 2009) showed that a ventilatory strategy comprising an ARM repeated every 10 minutes was associated with better intraoperative oxygenation and compliance.

The data collected in this study also confirmed that in dogs, the hemodynamic changes associated with CO_2-PP appear to be phasic, the adaptation mechanisms that occur in the first 10–20 minutes tending to compensate for the elevated IAP in healthy cardiovascular patients (O'Malley & Cunningham 2001; Zuckerman & Heneghan 2002). The development of elevated intrathoracic pressures and their impact on the hemodynamics of patients is one of the major limiting factors for the application of recruitment strategies (Tusman & Bohm 2010). Our results show that in healthy dogs, this may not be the case; nonetheless, we suggest always monitoring the major cardiovascular parameters of patients during a recruiting maneuver and being ready to support cardiovascular function with fluids and/or drugs if major side effects occur (marked hypotension and/or bradycardia). The human literature suggests that adequate cardiovascular stabilization is usually sufficient to counterbalance the hemodynamic effects of a recruitment strategy (Tusman & Bohm 2010).

Interestingly, our results demonstrated that the effects of intraoperative recruitment persisted after the resolution of PP (PPpost20), a time in which the RM group had better oxygenation and respiratory system compliance than occurred in the NO-RM group. Laparoscopy promotes further formation of atelectasis, a condition that has been proven to persist in the postoperative period and affect oxygenation and the incidence of pulmonary complications in human patients (Lindberg et al. 1992)). Similarly, Karsten et al. (Karsten et al. 2014) were able to demonstrate with electrical impedance tomography that an intraoperative recruitment strategy improves pulmonary ventilation distribution during the postoperative period in patients undergoing laparoscopic surgery. Thus, we may speculate that, even if was not specifically investigated in our study, an intraoperative recruitment strategy during PP reduces postoperative pulmonary atelectasis and thus should reduce the incidence of postoperative hypoxemia and other pulmonary complications in dogs. Further studies are required to confirm this hypothesis.

The limited number of animals included in this study can explain the greater variability observed for some parameters [Fshunt, Cst_{RS}, $P(a\text{-}E')CO_2$] in the RM group. Accordingly, our results need to be confirmed on a larger scale of clinical cases.

In conclusion, this study demonstrated that a vital capacity alveolar recruiting maneuver followed by 5 cmH2O PEEP improves lung function during and after CO_2-PP in healthy dogs undergoing laparoscopy. Moreover, the results of the study confirmed that $P(a\text{-} E')CO_2$ can be a useful parameter for monitoring alveolar collapse and recruitment during laparoscopy.

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Table 1 The mean ± standard deviation of the gas exchange parameters in 20 dogs undergoing laparoscopic surgery mechanically ventilated with (RM group, *n* = 10) or without (NO-RM group, *n* = 10) an alveolar recruiting maneuver (ARM) followed by the application of 5 cmH$_2$O PEEP. Data were collected before the creation of the pneumoperitoneum (PP, PPpre), 10 (PP10) and 30 (PP30) minutes after the beginning of the PP, and 20 minutes after its discontinuation (PPpost20). The ARM was performed immediately after the collection of the data at PP10. *$p < 0.05$ between the two groups at the same study time; #$p < 0.05$ compared with PPpre in the same group; °$p < 0.05$ compared with PP10 in the same group.

Parameter	Group	PPpre	PP10	PP30	PPpost20
PaO$_2$ mmHg (kPa)	**NO-RM**	368.8 ± 84.9 (49.1 ± 11.3)	392.3 ± 60.5 (52.3 ± 8.1)	376.8 ± 56.2 (50.2 ± 7,4)	341.6 ± 83.4 (45.5 ± 11.1)
	RM	359.8 ± 67.2 (47.9 ± 8.9)	394.3 ± 37.7 (52.5 ± 5.1)	505.4±31.7#°* (67.3±4.2)	450.9 ± 70.6#* (60.1 ± 9.4)
PaO$_2$:FIO$_2$ mmHg (kPa)	**NO-RM**	411.2 ± 34.3 (54.8 ± 4.5)	490.5 ± 75.6 (65.3 ± 10.1)	471.3 ± 70.3# (62.8 ± 9.3)	361.7 ± 37.5# (48.2 ± 4.9)
	RM	449.7 ± 84.1 (59.9 ± 11.2)	492.8 ± 47.2 (65.7 ± 6.2)	631.7±39.6#°* (84.2 ± 5.2)	563.6 ± 88.3#* (75.1 ± 11.7)
Fshunt (%)	**NO-RM**	10.01 ± 4.3	5.1 ± 1.6#	5.2 ± 2.1#	11.1 ± 5.2
	RM	10.9 ± 4.9	7.6 ± 2.8#	2.3 ± 2.2#°*	4.7 ± 3.7#*
SpO$_2$ (%)	**NO-RM**	98.5 ± 0.46	97.6 ± 1.3	97.5 ± 1.6	96.9 ± 1.2
	RM	97.6 ± 1.4	96.3 ± 2.2	99.3 ± 0.2	99.1 ± 0.4
PaCO$_2$ mmHg (kPa)	**NO-RM**	44.2 ± 7.5 (5.8 ± 0.9)	59.8 ± 11.2# (7.9 ± 1.4)	61.3 ± 9.3# (8.1 ± 1.2)	49.3 ± 7.4 (6.5 ± 0,9)
	RM	49.8 ± 5.4 (6.6 ± 0.7)	64.4 ± 7.3# (8.5 ± 0.9)	55.6 ± 5.8# (7.4 ± 0.7)	53.2 ± 9.6 (7.0 ± 1.2)

$P_{E'}CO_2$ mmHg (kPa)	**NO-RM**	38.2 ± 4.9 (5.1 ± 0.6)	46.1 ± 9.3# (6.1 ± 1.2)	46.4 ± 6.9# (6.1 ± 0.9)	43.8 ± 6.5 (5.8 ± 0.8)
	RM	45.1 ± 4.2 (6.1 ± 0.5)	50.2 ± 8.8# (6.7 ± 1.1)	50.1 ± 5.4# (6.7 ± 0.7)	47.1 ± 8.9 (6.2 ± 1.1)
$P(a-E')CO_2$ mmHg (kPa)	**NO-RM**	6.3 ± 1.2 (0.8 ± 0.1)	12.5 ± 2.2# (1.6 ± 0.3)	16.6 ± 6.5# (2.2 ± 0.8)	7.5 ± 3.4 (0.9 ± 0.4)
	RM	4.8 ± 6.2 (0.6 ± 0.8)	14.4 ± 7.7# (1.9 ± 1.1)	5.6 ± 3.9°* (0.7 ± 0.5)	6.1 ± 2.2 (0.8 ± 0.3)
pH	**NO-RM**	7.25 ± 0.02	7.19 ± 0.06	7.18 ± 0.05	7.25 ± 0.07
	RM	7.25 ± 0.05	7.15 ± 0.09	7.15 ± 0.07	7.28 ± 0.11

PaO_2, arterial partial pressure of oxygen; PaO_2:FIO_2, ratio of arterial oxygen partial pressure to inspired oxygen fraction; Fshunt, estimated intrapulmonary shunt; SpO_2, peripheral capillary oxygen hemoglobin saturation; $PaCO_2$, arterial partial pressure of carbon dioxide; $P_{E'}CO_2$, end-tidal carbon dioxide partial pressure; $P(a-E')CO_2$, arterial to end-tidal CO_2 gradient.

Table 2 The mean ± standard deviation of the respiratory system mechanics parameters in 20 dogs undergoing laparoscopic surgery mechanically ventilated with (RM group, $n = 10$) or without (NO-RM group, $n = 10$) an alveolar recruiting maneuver (ARM) followed by the application of 5 cmH_2O PEEP. Data were collected before the creation of the pneumoperitoneum (PP, PPpre), 10 (PP10) and 30 (PP30) minutes after the beginning of the PP, and 20 minutes after its discontinuation (PPpost20). The ARM was performed immediately after the collection of the data at PP10. *$p < 0.05$ between the two groups at the same study time; #$p < 0.05$ compared with PPpre in the same group; °$p < 0.05$ compared with PP10 in the same group.

Parameter	**Group**	**PPpre**	**PP10**	**PP30**	**PPpost20**
Ppeak (cmH_2O)	**NO-RM**	10.2 ± 2.2	13.6 ± 2.9#	13.8 ± 3.2#	10.4 ± 2.1
	RM	9.2 ± 1.8	11.4 ± 2.8#	16.9 ± 3.5#*	12.1 ± 1.6#*
Pplat (cmH_2O)	**NO-RM**	9.4 ± 2.5	13.1 ± 3.1#	13.6 ± 3.2#	9.6 ± 2.5
	RM	8.1 ± 1.1	10.1 ± 1.6#	14.5 ± 3.4#	11.2 ± 1.2#
Cst,$_{RS}$ (mL cmH_2O^{-1} kg^{-1})	**NO-RM**	1.4 ± 0.7	0.8 ± 0.1#	0.9 ± 0.4#	1.2 ± 0.2
	RM	1.7 ± 0.6	1.1 ± 0.2#	2.4 ± 0.2#°*	2.1 ± 0.4#*
f_R (breaths $minute^{-1}$)	**NO-RM**	12.3 ± 1.5	22.5 ± 2.1#	23.2 ± 2.1#	13.2 ± 2.5
	RM	14.2 ± 3.5	21.3 ± 3.1#	24.2 ± 1.4#	13.2 ± 2.2
$\dot{V}_E$ (L $minute^{-1}$ kg^{-1})	**NO-RM**	0.17 ± 0.02	0.21 ± 0.05#	0.22 ± 0.04#	0.23 ± 0.06#
	RM	0.16 ± 0.04	0.17 ± 0.03	0.24 ± 0.09#	0.25 ± 0.05#

Ppeak, peak airway pressure; Pplat, plateau airway pressure; Cst,$_{RS}$, static compliance of the respiratory system; f_R, respiratory rate; $\dot{V}_E$, minute volume.

Table 3 The mean ± standard deviation of the hemodynamic parameters in 20 dogs undergoing laparoscopic surgery mechanically ventilated with (RM group, $n = 10$) or without (NO-RM group, $n = 10$) an alveolar recruiting maneuver (ARM) followed by the application of 5 cmH_2O PEEP. Data were collected before the creation of the pneumoperitoneum (PP, PPpre), 10 (PP10) and 30 (PP30) minutes after the beginning of the PP, and 20 minutes after its discontinuation (PPpost20). The ARM was performed immediately after the collection of the data at PP10. *$p < 0.05$ between the two groups at the same study time; #$p < 0.05$ compared with PPpre in the same group.

Parameter	Groups	PPpre	PP10	PP30	PPpost20
HR	**NO-RM**	88.6 ± 25.3	103.1 ± 22.2#	100.9 ± 20.8	103 ± 24.3
(beats minute^{-1})	**RM**	82.2 ± 18.5	92.7 ± 11.2	93.4 ± 13.3	92.3 ± 8.2
MAP	**NO-RM**	77.5 ± 12.2	92.1 ± 25.2	88.7 ± 25.5	84.5 ± 21.1
(mmHg)	**RM**	76.2 ± 6.1	91.5 ± 9.6	82.7 ± 17.5	70.6 ± 2.8
CI	**NO-RM**	3.3 ± 1.2	2.4 ± 0.8#	3.1 ± 1.1	3.2 ± 1.3
(L minute^{-1} m^{-2})	**RM**	3.1 ± 1.2	2.4 ± 1.8#	3.1 ± 1.6	3.1 ± 1.6
SVR	**NO-RM**	2584.5±854.5	3105.6±1167.9	2833.3±1082.5	2719.0±890.5
(dyn × second × cm^{-5})	**RM**	3233±1958.9	3817.4±844.4	2755.8±1189.5	2993±1357.3

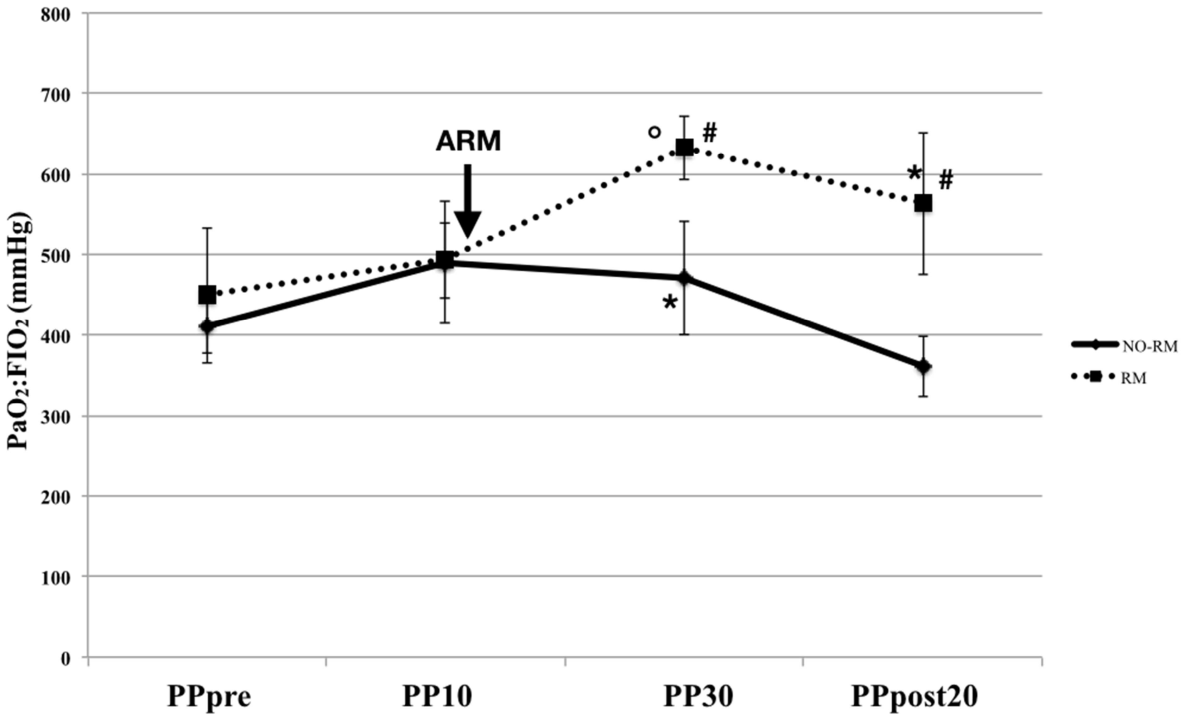
HR, heart rate; MAP, mean arterial pressure; CI, cardiac index; SVR, systemic vascular resistances

Figure 1 Graphical representation of the mean ± standard deviation values of the PaO_2:FIO_2 in 20 dogs undergoing laparoscopic surgery mechanically ventilated with (RM group, $n = 10$) or without (NO-RM group, $n = 10$) an alveolar recruiting maneuver (ARM) followed by the application of 5 cmH_2O PEEP. Data were collected before the creation of the pneumoperitoneum (PP, PPpre), 10 (PP10) and 30 (PP30) minutes after the beginning of the PP, and 20 minutes after its discontinuation (PPpost20). The ARM was performed immediately after the collection of the data at PP10 (arrow). *$p < 0.05$ between the two groups at the same study time; #$p < 0.05$ compared with PPpre in the same group.

Figure 2 Graphical representation of the mean ± standard deviation values of the estimated intrapulmonary shunt (Fshunt) in 20 dogs undergoing laparoscopic surgery mechanically ventilated with (RM group, $n = 10$) or without (NO-RM group, $n = 10$) an alveolar recruiting maneuver (ARM) followed by the application of 5 cmH_2O PEEP. Data were collected before the creation of the pneumoperitoneum (PP, PPpre), 10 (PP10) and 30 (PP30) minutes after the beginning of the PP, and 20 minutes after its discontinuation (PPpost20). The ARM was performed immediately after the collection of the data at PP10 (arrow). *$p < 0.05$ between the two groups at the same study time; #$p < 0.05$ compared with PPpre in the same group.

Figure 3 Graphical representation of the mean ± standard deviation values of the arterial to end-tidal CO_2 gradient [$P(a-E')CO_2$] in 20 dogs undergoing laparoscopic surgery mechanically ventilated with (RM group, $n = 10$) or without (NO-RM group, $n = 10$) an alveolar recruiting maneuver (ARM) followed by the application of 5 cmH_2O PEEP. Data were collected before the creation of the pneumoperitoneum (PP, PPpre), 10 (PP10) and 30 (PP30) minutes after the beginning of the PP, and 20 minutes after its discontinuation (PPpost20). The ARM was performed immediately after the collection of the data at PP10 (arrow). *$p < 0.05$ between the two groups at the same study time; #$p < 0.05$ compared with PPpre in the same group; °$p < 0.05$ compared with PP10 in the same group.

Figure 4 Graphical representation of the mean ± standard deviation values of the static compliance of the respiratory system ($Cst,_{RS}$) in 20 dogs undergoing laparoscopic surgery mechanically ventilated with (RM group, $n = 10$) or without (NO-RM group, $n = 10$) an alveolar recruiting maneuver (ARM) followed by the application of 5 cmH_2O PEEP. Data were collected before the creation of the pneumoperitoneum (PP, PPpre), 10 (PP10) and 30 (PP30) minutes after the beginning of the PP, and 20 minutes after its discontinuation (PPpost20). The ARM was performed immediately after the collection of the data at PP10 (arrow). *$p < 0.05$ between the two groups at the same study time; #$p < 0.05$ compared with PPpre in the same group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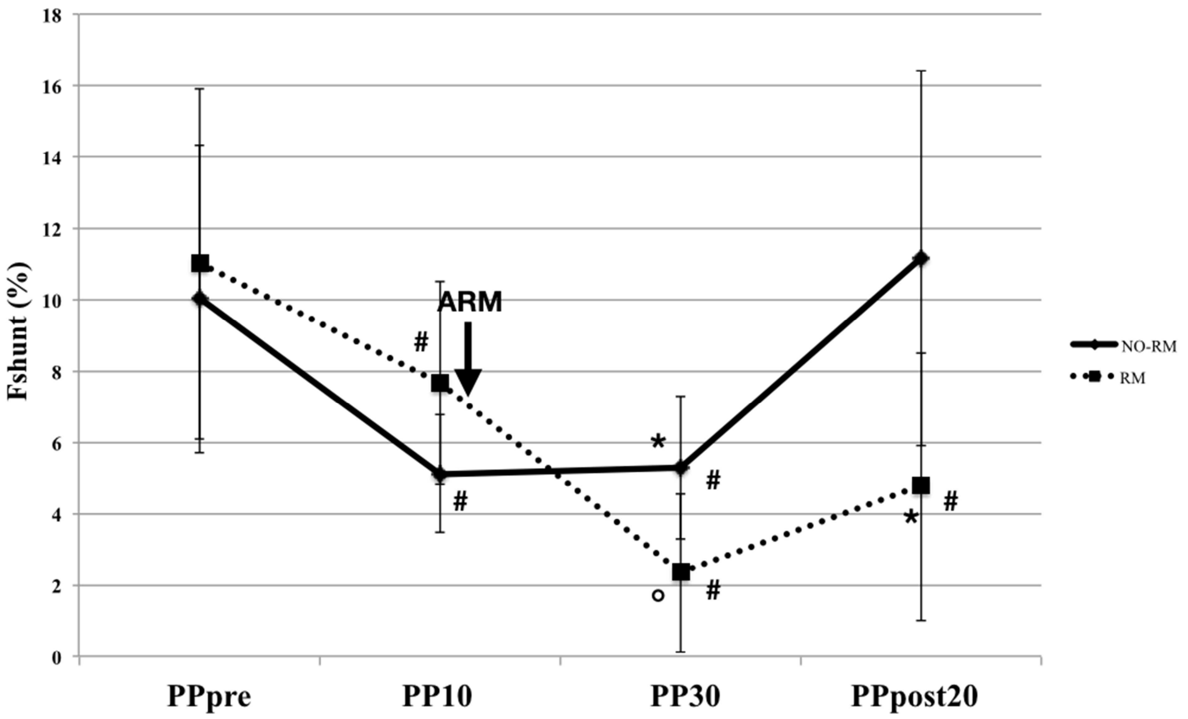
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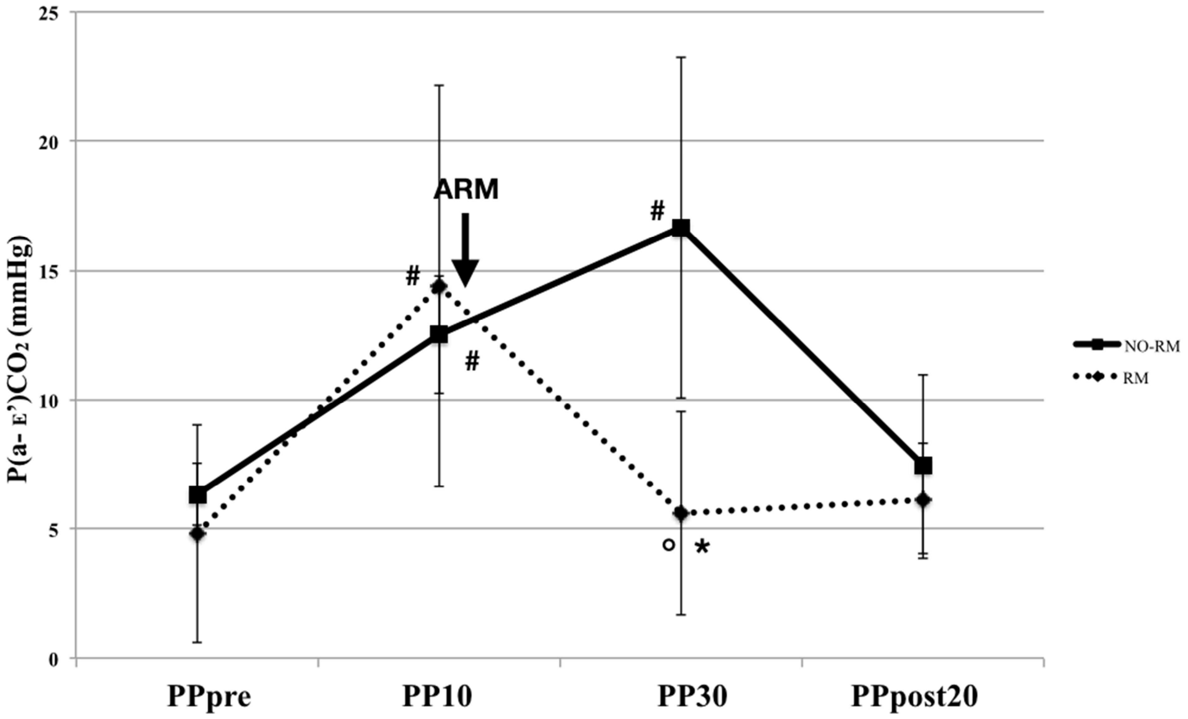
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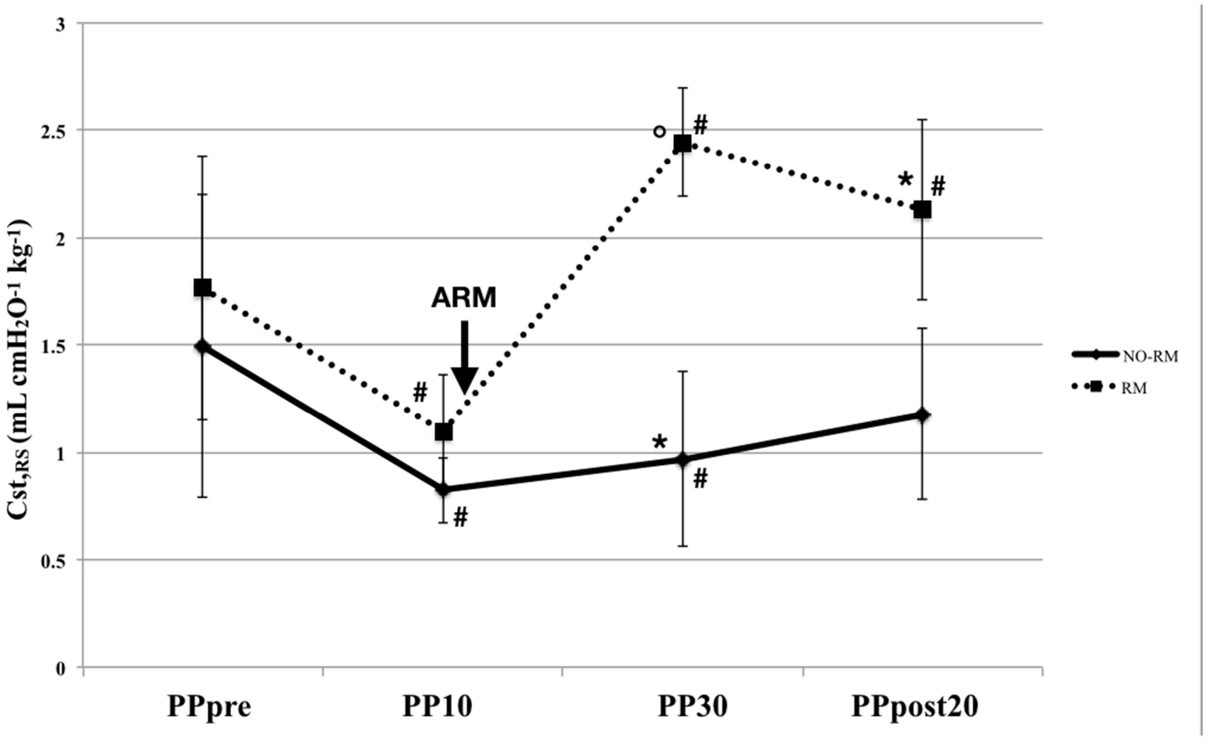
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