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Effects of continuous positive airway pressure administered by a helmet in cats under general anaesthesia

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Abstract

Objectives The aim of this study was to evaluate the respiratory effects of non-invasive continuous positive airway pressure (CPAP) administered by a helmet in healthy cats under anaesthesia.

Methods Fifteen healthy male cats scheduled for castration were anaesthetised with medetomidine (20 µg/kg), ketamine (10 mg/kg) and buprenorphine (20 µg/kg) intramuscularly. When an adequate level of anaesthesia was achieved, a paediatric helmet was placed on all subjects. The helmet was connected to a Venturi valve supplied with medical air and cats received the following phases of treatments: 0 cmH_2O (pre-CPAP), 5 cmH_2O (CPAP) and 0 cmH_2O (post-CPAP). Each treatment lasted 10 mins. At the end of each phase an arterial blood sample was drawn. The following data were also collected: mean arterial pressure, respiratory rate, heart rate and the anaesthesia level score (0 = awake, 10 = deep anaesthesia). The alveolar to arterial oxygen gradient (P[A-a]O_2) and the venous admixture (Fshunt) were also estimated. Data were analysed with two-way ANOVA ($P < 0.05$).

Results The arterial partial pressure of oxygen was higher ($P < 0.001$) at CPAP (103.2 ± 5.1 mmHg) vs pre-CPAP (77.5 ± 7.4 mmHg) and post-CPAP (84.6 ± 8.1 mmHg). The P(A-a)O_2 and the Fshunt were lower ($P < 0.001$) at CPAP (4.4 ± 2.3 mmHg; 7.4 ± 3.1%) vs pre-CPAP (18.9 ± 6.4 mmHg; 22.8 ± 4.6%) and post-CPAP (15.6 ± 7.3 mmHg; 20.9 ± 4.6 %). No other parameters differed between groups.

Conclusions and relevance Non-invasive CPAP applied by a helmet improves oxygenation in cats under injectable general anaesthesia.

Keywords: Continuous positive airway pressure; oxygenation; anaesthesia; atelectasis

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Introduction

General anaesthesia is associated with impaired gas exchange and altered respiratory system mechanics.[1] Atelectasis is common during muscle relaxation and with the use of high inspired oxygen fractions, even in cats.[2] High oxygen concentrations promote alveolar gas absorption and collapse in the area of the lung affected by low ventilation/perfusion ratios.[1,2] In patients breathing spontaneously without airway control, airway collapse and reduced minute ventilation further contribute to lung function impairment.[3] Inhibition of the hypoxic pulmonary vasoconstriction reflex may also contribute to gas exchange impairment, especially with the use of inhalant anaesthetics.[1] Non-invasive respiratory support (NRS) techniques provide breathing support without the

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need for tracheal intubation.[4] A common NRS mode that has been recently introduced in veterinary medicine is continuous positive airway pressure (CPAP).[5]

Using an interface, CPAP ensures a constant positive pressure throughout the entire respiratory cycle.[5] Several studies in people and, recently, in veterinary medicine, have demonstrated the feasibility of CPAP in improving lung function in the perioperative period.[5–8] The efficacy of CPAP has been shown in sedated dogs,[8] and in dogs recovering from general anaesthesia or affected by acute respiratory failure.[5,9] Another study showed that 5 cmH_2O CPAP almost doubled the laryngeal size in anaesthetised dogs using a helmet CPAP device.[10]

Similar to other species, sedation or anaesthesia can lead to airway collapse and atelectasis in cats.[2,11]

Although, in general, endotracheal intubation in cats can be accomplished easily, increased risk of major complications has been reported.[12,13] The airway in cats is small and delicate, and the larynx is susceptible to spasm, trauma or oedema when stimulated. Tracheal tears have been also reported.[11,12] Therefore, anaesthetic episodes associated with short procedures may be accomplished without intubation under close monitoring of oxygenation and ventilation.[12] In these circumstances, CPAP could be considered an adequate support in order to optimise lung function. Recovery from anaesthesia represents another condition where CPAP may be beneficial, especially in brachycephalic cats or in those with different airway or parenchymal pathologies. There are scarce literature describing the use of NRS in cats. Brown et al[14] reported the application of NRS in cats using a neonatal face mask. The authors identified several limitations for the clinical application of this mode of NRS, such as the need for a dedicated interface. The use of low levels of CPAP was described to treat acute upper airway obstruction successfully in a cat recovering from general anaesthesia.[15]

Compared with the face mask, the helmet CPAP device is characterised by a greater tolerability in children and newborns.[16] The helmet creates a sealing at the level of the neck, making it more versatile and adjustable to the different head and face conformations of veterinary species. Although helmet CPAP is well tolerated, it is not entirely free from adverse side effects and complications that may impair its use: intolerance to the device; rebreathing of carbon dioxide; haemodynamic impairment; and technical and equipment failure.[4,7]

The aim of this study was to evaluate the physiological effects of 5 cmH_2O of CPAP administered by a paediatric helmet in anaesthetised healthy cats undergoing elective orchiectomy. Our hypothesis was that the administration of CPAP would improve oxygenation vs breathing at atmospheric pressure.

Materials and methods

This study was approved by the Ethical Committee for Clinical Study in Animal Patients of the Department of Emergency and Organs Transplantation of the University of Bari, Italy (protocol 21/2015).

Patients

After written owner consent was obtained, healthy male cats undergoing elective orchiectomy, aged between 12 and 24 months, without cardiovascular or respiratory disease, or haematological or biochemical alterations, were included in the study. Cats requiring administration of additional drugs or treatments different to the protocol of the study (see below) were excluded. Cases in which arterial sampling was not possible at each study time were also excluded.

Anaesthetic protocol

Cats were premedicated with 20 µg/kg medetomidine (1 mg/ml Domitor; Orion), 10 mg/kg ketamine (100 mg/ml Ketavet; Intervet) and 20 µg/kg buprenorphine (0.3 mg/ml Buprenodale; Dechra) intramuscularly (IM). When sedation was deemed adequate, a cephalic vein was cannulated for intravenous (IV) fluid (5 ml/kg/h Ringer lactate solution) and drug administration. All cats received 1 mg/kg robenacoxib (20 mg/ml Onsior; Elanco) and 20 mg/kg amoxicillin/clavulanic acid (140 mg/ml Synulox; Zoetis) IM before surgery. Anaesthesia level was scored with a visual analogue scale (VAS), ranging from 0 (completely awake) to 10 (profound depth) based on the clinical assessment, including pedal reflex (on the hindlimbs) and body movements, together with variation in respiratory rate, arterial pressure and heart rate (HR) in response to the surgical stimulation. Anaesthesia was induced with 1–2 mg/kg propofol (10 mg/ml Propovet; Merial) IV given slowly to reach a surgical plane of anaesthesia (ie, absence of pedal reflex, jaw tone and body movements). Additional propofol boluses (1–2 mg/kg) were administered throughout the procedure, when the level of anaesthesia was deemed light (VAS <7; ie, presence of pedal reflex and spontaneous movement of any part of the body).

A 22 G catheter was placed in one of the femoral arteries and connected to an arterial pressure transducer (TrueWave; Edwards) for direct monitoring of arterial pressure. The pressure transducer was zeroed at the level of the heart. Monitoring (SC 600XL; Siemens) included HR (beats/min); systolic, mean (MAP) and diastolic arterial pressure (mmHg); respiratory rate (RR; breaths/min); peripheral capillary oxygen haemoglobin saturation (SpO_2; %); temperature (T°; °C); and depth of anaesthesia. A neonatal CPAP helmet was placed in all cats after the arterial catheter was secured. Surgery started thereafter. Cats were allowed to breath room air during the entire procedure. Cats with an SpO_2 <90% and/or those that developed apnoea were immediately intubated and excluded from the study. Surgery was performed by a senior veterinary student assisted by an experienced veterinary surgeon. Heating support was provided throughout the procedure.

Study protocol

When an adequate level of anaesthesia was achieved, a neonatal helmet (CaStar; StarMed), with an internal volume of 7 l, was applied to all cats. Cats were positioned with the head, neck and front limbs inside the helmet, with the silicon collar sealed at the scapular level (Figure 1). A high flow of fresh gas was directed to the helmet through a calibrated Venturi valve. For the purposes of our study, the system was connected exclusively to a medical air source, in order to maintain a constant fraction of inspired oxygen (FiO_2) of 0.21. The Venturi valve was supplied with 8 l/min of medical air, generating approximately 40 l/min of fresh gas flow after passing through the valve (as indicated by the manufacturer).

All cats underwent three, 10 min phases of respiratory support during the same anaesthetic episode based on an off–on–off protocol. During the first phase cats were kept inside the helmet with a CPAP level of 0 cmH_2O (pre-CPAP phase). This condition was obtained by removing the CPAP valve from the helmet. In the second phase, the CPAP level was maintained at 5 cmH_2O, adjusting the CPAP valve (CPAP phase; Figure 1). In the third phase the CPAP level was returned to 0 cmH_2O (post-CPAP phase).

At the end of each phase, HR, RR, T° and depth of anaesthesia (VAS score) were recorded and an anaerobically collected arterial blood sample obtained and immediately analysed (VetStat; IDEXX Laboratories). The following parameters were recorded: arterial partial pressure of oxygen (PaO_2) and carbon dioxide ($PaCO_2$), pH and arterial oxygen saturation (SaO_2). The PaO_2 to FiO_2 (PaO_2/FiO_2) ratio was calculated. Additionally, the alveolar partial pressure of oxygen (PAO_2) was calculated using the following formula:

$$PAO_2 = \left(\left[Pb - PH_2O\right] \times FiO_2\right) - \left(PaCO_2/R\right) \quad (1)$$

where Pb is the barometric pressure, PH_2O is the water vapour pressure (based on the patient's body temperature) and R represents the respiratory quotient (0.9 in cats).[2]

The alveolar–arterial oxygen gradient was calculated as:

$$P(A-a)O_2 = PAO_2 - PaO_2 \quad (2)$$

The venous admixture (Fshunt) was calculated as follows:[17]

$$Fshunt = \left(\frac{\left[Cc'O_2 - CaO_2\right]/}{\left[Cc'O_2 - CaO_2 + 3.5\ mldl^{-1}\right]}\right) \times 100 \quad (3)$$

where $Cc'O_2$ is the pulmonary end-capillary oxygen content, CaO_2 is the arterial oxygen content and 3.5 ml/dl is an approximate fixed value representing the arterial-to-mixed venous oxygen content difference. $Cc'O_2$ and CaO_2 were calculated as follows:

$$Cc'O_2 = Hb \times 1.39 \times Sc'O_2 + 0.003 \times Pc'O_2 \quad (4)$$

$$CaO_2 = Hb \times 1.39 \times SaO_2 + 0.003 \times PaO_2 \quad (5)$$

where Hb is the haemoglobin concentration (g/dl), 1.39 is the oxygen-carrying capacity of haemoglobin (ml/g) in cats,[18] $Sc'O_2$ is the pulmonary end-capillary oxygen saturation, 0.003 is the solubility coefficient of oxygen in plasma 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.

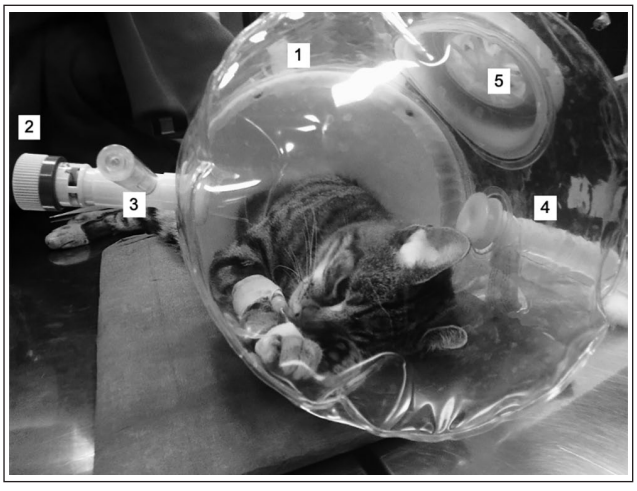

Figure 1 Equipment used to provide non-invasive continuous positive airway pressure (CPAP) in cats under general anaesthesia. The helmet (1) is equipped with an inlet (4) and outlet gas port with the CPAP valve (2). In the picture is possible to observe the manometer (3) to monitor the pressure inside the helmet and the anti-asphyxia valve (5)

Statistical analysis

A sample size calculation was performed considering previous data in dogs,[5] and an estimated clinically relevant variation in PaO_2 of 10%. Power calculation was conducted for a two-tailed *t*-test with a power of 0.95 and an alpha error of 0.05 (G*Power Version 3.1.9.3). This suggested that a minimum of 13 cats would be sufficient to detect significant differences among treatments in a crossover off–on–off protocol.

Statistical analysis was performed using MedCalc software 9.0. Data were reported as mean ± SD. Parametric data were analysed with two-way ANOVA for repeated measurements and the Tukey post-hoc test. Non-parametric data were analysed with the Friedman and Dunnet test. A P value <0.05 was considered to be statistically significant.

Table 1 Clinically relevant parameters in 15 cats included in the study

Parameters	Pre-CPAP	CPAP	Post-CPAP
Heart rate (beats/min)	144 ± 27.5	139 ± 38.3	121 ± 27.3
Respiratory rate (breaths/min)	22 ± 10.6	26 ± 7.4	26 ± 7.8
SpO_2 (%)	95.3 ± 1.8	98.3 ± 0.8	95.6 ± 1.3
Mean arterial pressure (mmHg)	98.5 ± 8.3	92.3 ± 5.4	101.3 ± 8.2
Temperature (°C)	38.6 ± 0.6	37.8 ± 0.8	37.6 ± 0.9
Depth of anaesthesia	8.7 ± 0.9	9.2 ± 0.8	8.5 ± 1.2

Data are mean ± SD. Each cat received three different consecutive levels of continuous positive pressure (CPAP) through a paediatric helmet: pre-CPAP = 0 cmH_2O; CPAP = 5 cmH_2O; post-CPAP = 0 cmH_2O
SpO_2 = peripheral capillary oxygen haemoglobin saturation

Table 2 Gas exchange parameters during general anaesthesia in 15 cats included in the study

Parameters	Pre-CPAP	CPAP	Post-CPAP
PaO_2 (mmHg)	77 ± 7.4	103 ± 5.1*	84 ± 8.1
PaO_2:FiO_2 (mmHg)	366.45 ± 40.5	481.3 ± 23.5*	392.2 ± 120.3
SaO_2 (%)	96.3 ± 1.2	99.2 ± 0.3*	95.4 ± 1.5
Fshunt (%)	22.86 ± 4.6	7.46 ± 3.03*	20.93 ± 4.6
P(A-a)O_2 (mmHg)	18.9 ± 6.4	4.45 ± 2.3*	15.6 ± 7.3
$PaCO_2$ (mmHg)	39.2 ± 6.1	40.1 ± 6.8	40.3 ± 9.9
pH	7.33 ± 0.05	7.34 ± 0.04	7.34 ± 0.08

Data are mean ± SD. Each cat received three different consecutive levels of continuous positive pressure (CPAP) through a paediatric helmet: pre-CPAP = 0 cmH_2O; CPAP = 5 cmH_2O; post-CPAP = 0 cmH_2O
*P <0.05 compared with pre- and post-CPAP
PaO_2 = arterial partial pressure of oxygen; FiO_2 = fraction of inspired oxygen; SaO_2 = arterial oxygen saturation; Fshunt = venous admixture; P(A-a)O_2 = alveolar to arterial oxygen gradient; $PaCO_2$ = arterial partial pressure of carbon dioxide

Results

After owner written consent was obtained, 22 cats were included in the study. Seven cats were excluded – two because of the need for extra drugs during the peri-anaesthetic period and five because it was not possible to get an arterial sample during all study times. Fifteen cats completed the study. The mean ± SD values of weight and age were 3.9 ± 0.7 kg and 12.1 ± 2.8 months, respectively. Duration of surgery was 38.8 ± 5.3 mins and all procedures were completed without complications. All cats breathed room air during the entire procedures and never required oxygen supplementation. The average ± SD total dose of propofol administered during the entire procedure was 5.6 ± 2.2 mg/kg.

HR, RR, MAP, SpO_2, T° and VAS score did not differ significantly between the three phases of the study (P >0.05, Table 1).

The PaO_2, PaO_2/FiO_2 and SaO_2 were significantly higher (P <0.01) in the CPAP phase compared with the other phases. The alveolar to arterial oxygen gradient (P[A-a]O_2) and the Fshunt were significantly lower (P <0.01) during CPAP compared with the other phases. $PaCO_2$ and pH did not differ significantly (P >0.05) between the three phases (Table 2 and Figure 2).

Discussion

The results of this study showed that the application of 5 cmH_2O of CPAP through a paediatric helmet is effective at increasing the oxygenation in anaesthetised and/or deeply sedated cats during short surgical procedures.

General anaesthesia is associated with several respiratory and cardiovascular alterations that can lead to reductions in oxygenation.[1] Our group has previously shown that pulmonary atelectasis occurs in cats under general anaesthesia and is aggravated by the use of high FiO_2.[2] Collapsed and poorly aerated alveoli develop in the most dependent areas of the lungs and contribute to the development of venous admixture.[5,19] Airway collapse and diaphragmatic muscle relaxation are regular effects of general anaesthesia, which, coupled with unnatural recumbencies, also contribute to impaired gas exchange.[20,21] Importantly, these anaesthetic changes lead to a reduction of the respiratory system compliance and an overall increase in the work of breathing.[22] Our

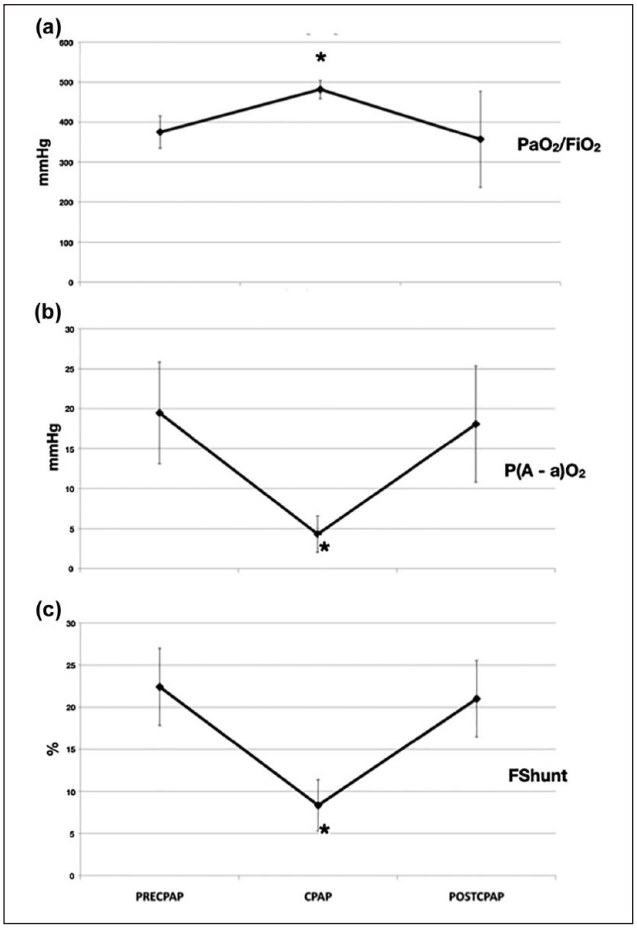

Figure 2 Effect of continuous positive airway pressure (CPAP) on different oxygenation indices. Mean ± SD values of (a) arterial partial pressure of oxygen (PaO_2)/fraction of inspired oxygen (FiO_2), (b) alveolar to arterial oxygen gradient ($P[A\text{-}a]O_2$) and (c) venous admixture (FShunt) in 15 cats during general anaesthesia. Each cat received three different consecutive levels of CPAP through a paediatric helmet. Pre-CPAP = 0 cmH_2O; CPAP = 5 cmH_2O; post-CPAP = 0 cmH_2O, *P <0.05 compared with pre- and post-CPAP

data suggest that, despite maintaining an adequate SpO_2, non-intubated, anaesthetised cats breathing room air have abnormal oxygenation indices vs the awake condition.[18,23]

The reduction in oxygenation efficiency (decreased SaO_2 and PaO_2/FiO_2) seen during the pre- and post-CPAP phases was probably related to an increase in venous admixture, as suggested by the increased Fshunt levels, and not to a ventilation deficit, as values of $PaCO_2$ stayed within normal limits. Administration of 5 cmH_2O of CPAP resulted in rapid normalisation of all these oxygenation indices.[18,23] Although further studies are required to prove this hypothesis in cats, it is possible that the overall improvement in oxygenation indices is related to a better maintenance of small airway patency and alveolar recruitment during CPAP. The physiological effects of CPAP have been investigated in several studies in human and veterinary patients.[24,25] CPAP works mainly on the upper and lower airways by increasing their diameter and reducing the occurrence of anaesthesia-related airway collapse.[4] The net effect is a reduced airway resistance and work of breathing, promoting greater thoracic expansion and recruitment of atelectatic tissue, with a consequent improvement of gas exchange.[26,27] In anaesthetised dogs, CPAP increases the functional residual capacity, as assessed by electrical impedance tomography.[24,28]

The crossover design of this study, with an off–on–off sequence, allowed us to identify the effects of CPAP on gas exchange. There was a clear improvement in oxygenation with the application of CPAP and a subsequent deterioration when it was removed during the post-CPAP phase. This oxygenation pattern confirms that the observed effects were related to the application of CPAP and not to temporal effects associated with the anaesthetic events. In fact, the depth of anaesthesia and physiological parameters were similar in all phases of the study. Additionally, the FiO_2 was maintained constant at 0.21 throughout the study; consequently, the improvement in oxygenation was related to the pure effects of CPAP and not to oxygen supplementation. On this topic, we should clarify that the use of air as supplemental gas was related to the purposes of the study in order to have a more robust evaluation of the gas exchange parameters, keeping the FiO_2 constant and known at each phase of the study. For clinical applications CPAP should always be provided with a helmet supplied with oxygen, as indicated by the manufacturer.

The present study was designed as a proof-of-concept study and not to suggest that the helmet should replace orotracheal intubation, as the latter is the most effective and safe way to control the airways and to ensure optimal ventilatory support in anaesthetised cats. However, the results of this study are encouraging and should be considered as initial evidence that the administration of CPAP may be an adequate and non-invasive alternative to orotracheal intubation to provide ventilatory support for procedures requiring deep sedation/anaesthesia. Helmet CPAP could also be considered a useful support to respiratory function during the postoperative period and in cats affected by respiratory disfunction due to respiratory diseases, although these specific situations require further validation studies. The lack of an adequate interface for cats should be considered the major current limitation for the application of CPAP in cats and further studies should investigate the efficacy of dedicated interfaces able to guarantee the tolerance of CPAP application in lightly sedated or awake cats. Because of the clinical nature of this study, it was not possible to perform more advanced respiratory monitoring, such as thoracic

imaging or measurement of respiratory mechanics, that could provide useful information about the effects of CPAP on the respiratory system of anaesthetised cats.

Conclusions

The results of this study confirmed the efficacy of the helmet system in delivering CPAP and improving oxygenation indices in healthy cats during short surgical procedures. If these data are confirmed in a larger population of anaesthetised cats, helmet CPAP could become an important therapeutic option for non-invasive respiratory support in cats with respiratory dysfunction. Further studies should evaluate the efficacy of different interfaces that could result in better tolerance to CPAP in lightly sedated or awake cats.

Conflict of interest The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Ethical approval This work involved the use of non-experimental animals (owned or unowned) and procedures that differed from established internationally recognised high standards ('best practice') of veterinary clinical care *for the individual patient*. The study therefore had ethical approval from an established committee as stated in the manuscript.

Informed consent Informed consent (either verbal or written) was obtained from the owner or legal custodian of all animal(s) described in this work (either experimental or non-experimental animals) for the procedure(s) undertaken (either prospective or retrospective studies). For any animals or humans individually identifiable within this publication, informed consent (either verbal or written) for their use in the publication was obtained from the people involved.

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