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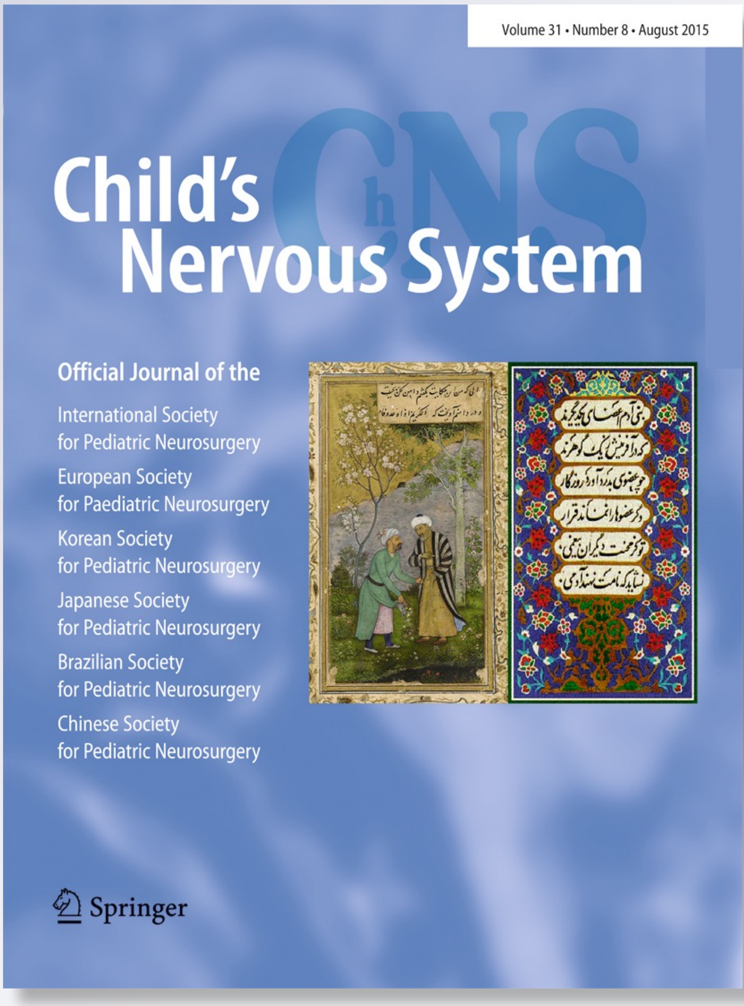

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ORIGINAL PAPER

Carbon dioxide field flooding reduces the hemodynamic effects of venous air embolism occurring in the sitting position

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Abstract
Purpose Although the utility of the sitting position is undisputed for biomechanical and ergonomic reasons, it has been debated in recent years for its risks, particularly venous air embolism (VAE). In order to reduce the hemodynamic effect of VAE, we changed the composition of the surgical field air partially replacing nitrogen with carbon dioxide (CO_2) that better dissolves in human tissues.
Methods First, we tested our method on a test dummy in the sitting position. Infrared CO_2 sensors were placed close to the wound opening and on the facial mask of the surgeon. An oxygen sensor was connected to a computer for data recording (ALTAIR®, MSA Safety). This model showed that 10 L/min CO_2 flow provides efficient air displacement, maintaining safety for the surgeon. We reproduced the above-described surgical field environment in ten consecutive cases of posterior fossa surgery performed in the sitting position. A homogeneous group of ten patients operated in the sitting position with standard setting environment was used for control. We intraoperatively monitored VAE with trans-esophageal echocardiography (TEE), end-tidal CO_2 ($ETCO_2$), CO_2 arterial pressure ($PaCO_2$), and hemodynamic changes.
Results Although the percentage of VAE was 70 % in both groups, hemodynamic effects occurred in 10 % of cases in the study group and in 40 % of cases in the control group.
Conclusions Our preliminary study shows that a CO_2-enriched sitting position surgical microenvironment significantly reduces the hemodynamic effects of VAE, more likely because arterial CO_2 emboli are more soluble and consequently much better tolerated than air emboli.

Keywords CO_2 · Sitting position · Venous air embolism · End-tidal CO_2 · CO_2 arterial pressure · Hemodynamic changes

Introduction

The value of the sitting position for the operative approaches to the posterior fossa, pineal region, and superior cervical canal is well-known among neurosurgeons. Two of its main advantages are an optimal biomechanical condition of intracranial compartments of the patients and an ideal ergonomic position for the surgeons. However, despite several studies confirming its relative safety, the sitting position is burdened by significant complications that, according to some authors, even balance the aforementioned advantages [1–13].

Besides the almost constant pneumocephalus, venous air embolism (VAE) is the most common and feared adverse event [14]. Furthermore, the not rare patency of the foramen ovale increases the risks of paradoxical arterial air embolism, which can lead to myocardial and hemodynamic dysfunction, arrhythmia, and secondary brain damage [15–18]. Transesophageal echocardiography (TEE), analysis of carbon dioxide arterial partial pressure ($PaCO_2$), and capnography (end-tidal CO_2, $ETCO_2$) are the standard systems to directly or indirectly detect air embolism during neurosurgical procedures in the sitting position. However, also this sophisticated monitoring as many other more traditional maneuvers and tricks may not be sufficient once the air emboli entered the venous system [3, 5, 7, 11, 19].

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In order to reduce the VAE harms and to promote a safer use of the sitting position, we thought to change the quality of the air that composes the microatmosphere in the surgical field, and thus changing the quality of air eventually entering into the venous system. To this purpose, we replaced a part of the preeminent nitrogen (about 78 % of the atmospheric air) that our body cannot absorb with the carbon dioxide (CO_2) that excellently dissolves in human tissues.

Intraoperative CO_2 flooding is not a novelty. It has been used in cardiac surgery since the 1950s, with the aim of reducing the potential VAE episodes which are an important source of cerebral and myocardial microembolization during heart surgical procedures [20–22]. The idea of changing the atmosphere air composition using CO_2 is based on the fact that this gas is 25 times more soluble in tissues and blood than air, where its normal percentage is extremely low (0.05 %). A logarithmic increase of the amount of CO_2 in the potential inflowing air emboli could accelerate their absorbability by tissues. CO_2 is then rapidly discharged through the exhaled air.

The purpose of this study is to transfer this ingenious method devised by cardiac surgeons to neurosurgery for the approaches to the posterior fossa. In particular, we aim to assess the direct and indirect effects of CO_2 insufflation at different flow-rates on the clinical consequences of venous air embolism during operations in the sitting position. We hypothesize a consequent reduction of both injuries and hemodynamic effects caused by a persistent pulmonary or arterial obstruction.

Materials and methods

Pre-clinical testing

The first measurements were made on a test dummy, placed on a sitting position. We created a median concave space mimicking the posterior fossa surgical field, which is perpendicular to the floor. Standard drapes were used to limit the surgical field. We calculated the distance between the surgeon and the operative field considering also the space occupied by the microscope. Vertical laminar flows from the roof were regulated according to the institutional rules. A hose supplied with additional lateral holes conveyed the CO_2 from the CO_2-tank to the surgical field. The extremity of the hose is pierced and secured to the border of the wound. The holes on the hose direct the CO_2 to the inner part of the surgical field (Figs. 1 and 2). We insufflated CO_2 in order to increase its concentration, at the same time measuring both the CO_2 increase in the posterior fossa surgical field and the O_2 partial pressure reduction in the surgeon breathed air for safety reasons.

Although air is a mixture of several gases, including nitrogen and oxygen (20.95 % at sea level), atmospheric air acts as one gas at normal atmospheric pressure and temperature. As nitrogen is difficult to detect, the measure of the content of either CO_2 or O_2 in the surgical field can estimate air displacement due to CO_2 insufflation. Avogadro's law states "at constant pressure and temperature equal volumes of different gases contain equal amounts of gas molecules." This means that for every five CO_2 molecules that are supplied to a cavity, five air molecules are displaced, of which approximately one is an O_2 molecule. Thus, when the content of one of the gases is measured, the content of the other gases are indirectly measured as well.

In our experimental tests, we used an oxygen sensor with a heated ceramic element as a control sensor, and a carbon

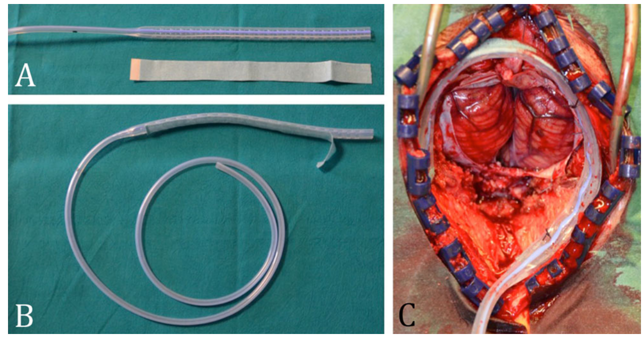

Fig. 1 **A** Disposable drainage flat catheter and adhesive strip are used to make a hose with holes on one side (**B**). **C** The catheter is secured to the wound in order to convey CO_2 to the surgical field. The side of the catheter that is not covered by the adhesive strip faces the surgical field

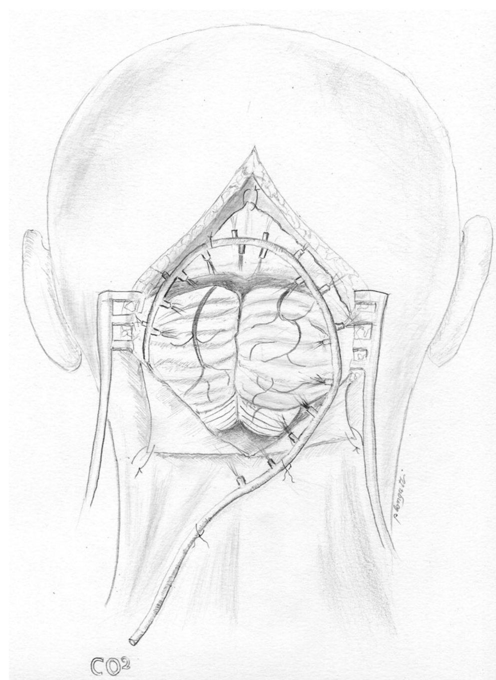

Fig. 2 Artist's drawing showing a better-designed model of CO_2 insufflation device. A hose supplied with additional lateral holes conveys the CO_2 from the CO_2-tank to the surgical field. The extremity of the hose is pierced and secured to the border of the wound

dioxide sensor with the infrared technique. The oxygen sensor is based on electrochemical sensors. It can assess air displacement more accurately and faster than the commonly used carbon dioxide sensors that use an optical infrared sensor technique to measure 0–100 % carbon dioxide. The oxygen sensor accuracy was 1 % of the measured value in the range 0.0001–100 % oxygen, which means that the accuracy increases as oxygen and air contents decrease. Moreover, the oxygen sensor requires only 2 mL gas sample volume and has a response time of less than 2 s.

The CO_2 sensors using the infrared technique usually have less accuracy than the O_2 sensors and require larger sampling volume and longer response time. The quick response modality of the O_2 sensor enabled the detection of rapid variations of air content over time. For this reason, we considered the O_2 sensor more suitable than optical infrared CO_2 sensors for evaluation of CO_2 removal during steady state and during changes of air composition. The sampling probe of the O_2 sensor is a 1.5-mm thick polytetrafluoroethylene tube. The remaining air content was measured at the highest and lowest point of the wound opening, close to the sites of the dura mater sinuses, which represent the main entry points for air embolism. A second CO_2 sensor was positioned laterally to the facial mask of the surgeon to analyze the composition of breathed air and give alarm when safety ranges are exceeded. The oxygen-measuring instrument was connected to a computer for data recording (ALTAIR®, MSA Safety).

The oxygen concentration was recorded for 5 s every minute (5/60 s). This model showed that 10 L/min CO_2 flow provides efficient air displacement in a posterior fossa surgical field model, with a mean O_2 decrease from 21 to 7–8 %. Similarly, also nitrogen is likely reduced to about 30 %. As a consequence, we indirectly calculated a CO_2 increase in the surgical field of about 152×10^3 %. Nonetheless, within these values, the safety limit for the surgeon was maintained with a $PaCO_2$ inferior to the security value (threshold limit value-time weighted average, TLV-TWA) of 5000 ppm [23].

Clinical cases

We recreated the above-described surgical field environment in ten consecutive cases of posterior fossa surgery performed in 2012 in the sitting position to remove seven vestibular schwannomas, two fourth ventricular ependymomas, and one pineal pilocytic astrocytoma. The cases were compared with a homogeneous control group of ten patients operated in the sitting position in 2011 for posterior fossa tumors, with standard setting environment. Patients of both the study group and the control group underwent echocardiography before surgery to detect any foramen ovale defect [24]. The exam was positive only in two patients of the control group (a meningioma of the foramen magnum and a ponto-cerebellar schwannoma), and in one case of the study group, a 17-year-old female with a pineal pilocytic astrocytoma.

We intraoperatively monitored VAE with trans-esophageal echocardiography (TEE), $ETCO_2$, $PaCO_2$, and hemodynamic changes: heart rate (HT) and systolic blood pressure (SBP).

To establish the severity of VAE, we measured the area occupied by air bubbles inside the right atrium at the echocardiography monitor and divided the embolic phenomenon into three levels of severity:

1. The presence of solitary bubbles with a bubble area <10 % of the right atrium is considered a mild VAE.
2. The presence of a bubble area occupying 10–50 % of the right atrium area is considered a moderate VAE.
3. The presence of a bubble area occupying more than 50 % of the right atrium area is considered a severe VAE.

We considered only the amount of air in the right atrium because the intraoperative monitoring was performed using the sonographic window ME BIC AV AL (midesophageal bicaval view). This kind of view allows a good vision of atria, interatrial septum, superior and inferior cava veins, right pulmonary artery, and right superior pulmonary vein. In this way, it is possible to detect even the minor embolic phenomena, being able to perform the corrective maneuvers to block the bubbles entrance into the right ventricle. The TEE warning is immediate not only in case of massive VAE but also when small solitary bubbles are present (Table 1).

For each embolic event registered with TEE, we recorded the pre-embolic value and the post-embolic value of HR, SBP, $ETCO_2$, and $PaCO_2$. An $ETCO_2$ decrease >3 mmHg and a SBP decrease >25 % were considered significant. The intraoperative monitoring was then compared between the two groups.

Results

Seven out of ten patients in the study group had episodes of VAE detected with TEE (70 %), but six of them had only mild/moderate adverse events without hemodynamic effects. The percentage of VAE with hemodynamic effects was 10 % in the study group. Patient number 4 had three episodes of VAE with two mild events and one severe event with changes in HR, SBP, $ETCO_2$, and $PaCO_2$ (Table 1).

Similarly, the percentage of VAE was 70 % in the control group. In the control group, the percentage of VAE with hemodynamic effects was 40 %. Three patients had mild adverse events, while three patients had moderate events with clear changes in HR, SBP, $ETCO_2$, and $PaCO_2$. Luckily, only one patient experienced a severe episode, but the hemodynamic effects where well tolerated (Table 1).

Table 1 VAE detections with TEE in ten patients who underwent posterior fossa surgery in the sitting position with high CO_2 concentration in the surgical field (1–10: study group; 11–20: control group)

	Patient	VAE			Heart rate (% change)	SBP (% change)	$ETCO_2$ (% change)	$PaCO_2$ (% change)
		Mild	Moderate	Severe				
Study group	1	X			+3	−1.8	−23	+7.4
	2							
	3		X		+1.6	−1.6	+11.5	+7.1
	4			X	+116.6	−39.1	−19.4	−21.2
	5	X			+2.9	−1.8	+3.8	+31.8
	6		X		+4.3	−1.7	0	−2.6
	7							
	8		X		+3	−0.8	0	+5.6
	9	X			+3.2	−1.6	+3.8	+7.1
	10							
Control group	11	X			+2.9	−1.8	+3.8	+31.8
	12	X			+11.2	−0.8	+3.7	0
	13			X	+37.7	−33.9	−18.5	−19
	14		X		+118.7	−43.5	−18.5	−21.2
	15							
	16							
	17		X		+44.3	−34.5	−27.6	−18.8
	18		X		+7.7	−15.3	+3.8	+7.1
	19							
	20	X			+3.1	0.8	0	+5.6

VAE venous air embolism, *TEE* trans-esophageal echocardiography, *$ETCO_2$* end-tidal carbon dioxide, *$PaCO_2$* carbon dioxide partial pressure in arterial blood, *SBP* systolic arterial pressure

Discussion

The use of the sitting position in neurosurgery has been and remains a controversial issue due especially to the risk of VAE and severe hemodynamic adverse events. The incidence of VAE is high (up to 70 % of patients) with a relatively low morbidity, and incidence of severe VAE producing hypotension ranges between 1 and 6 %. Many authors claim additional risks against the sitting position, particularly the rare but severe acute epidural hematoma formation, the increased rate of intracranial infection, and the severe postoperative pneumocephalus caused by the abundant CSF drainage, which might also be associated with headache and seizures. Moreover, the surgeon stays in a physically uncomfortable position, which makes it difficult to keep hands stable during the operation.

In our opinion, the sitting position remains a valuable approach to the pineal region and fourth ventricle-posterior fossa despite its risks. In pediatric neurosurgery, the sitting position is particularly precious because tumors are often located in the posterior fossa. Other approaches as the interhemispheric transtentorial performed in the supine position can be acceptable but do not offer the view and the trajectory provided by the infratentorial supracerebellar approach in the sitting position. This position is unique as it allows the use of both hands in dissecting, cutting, and debulking tumors and helps the drainage of blood and other fluids because of gravity. Therefore, there is no need for continuous aspiration, and an optimal microsurgical view over critical areas of the brainstem can be obtained. Of course, a really tight cooperation between the surgical and anesthesiology teams is necessary to reduce the severe hemodynamic risks of this kind of surgery.

Currently, VAE can be detected with the trans-esophageal Doppler, the analysis of $PaCO_2$, and capnography. However, a central venous catheter positioned close to the superior vena cava junction with the right atrium is the only device to prevent and treat major events by aspiration of intravascular air. The Valsalva maneuver is routinely used to promptly stop intravenous air, allowing the surgeon to notice any venous blood ooze and to arrange the best treatment using water irrigation, coagulation, or placement of hemostatic materials. In our experience, although the jugular compression causes a slight venous hypertension useful to stop air entrance, the following decompression might cause air suction into the venous system, as shown by trans-esophageal Doppler monitoring.

We perform preoperative contrast echocardiography for patent foramen ovale detection to all patient candidates for sitting position, and we use the intraoperative transesophageal Doppler ultrasonography to detect intracardiac air. However, in an attempt to improve the safety of the sitting position, we transferred to neurosurgery the cardiosurgical experience with the use of CO_2 in the surgical field. Many conventional devices for CO_2 insufflation are available for cardiothoracic surgery, and literature reports several considerations on airflow, turbulence, and entrainment. Experimental studies on cardiothoracic surgical field models have shown that the percentage of air left in the pericardial wall with simple open-end tubes delivering CO_2 is extremely variable, attaining till the 96 %. The optimal CO_2 delivery device reported in the literature is a gas diffuser insufflating at least 5 L/min with outflow velocity <0.1 m/s to avoid turbulence.

In the neurosurgical sitting position, it is not necessary to de-air the surgical cavity, whose plan is upright. In order to create an environment with high CO_2 concentration, the CO_2 flow must be strong enough to counteract the laminar flows and the air already present in the cavity. The model we set is very simple and effective. With a CO_2 flow of 10 L/min, the gas diffuser provides efficient air displacement in the posterior fossa cavity model, with a mean O_2 decrease from 21 to 7–8 %. The maintenance of this flow for about 1 h, which is the estimated time for posterior fossa opening, guarantees a $PaCO_2$ inferior to the security value (TLV-TWA) of 5000 ppm and preserves the safety of surgeons.

Our results show that higher CO_2 concentrations in the surgical field do not change the number of venous air embolism events because CO_2 doesn't change the rate of bubbles entrance in the venous sinuses. Nonetheless, the hemodynamic effects are significantly reduced, and this could be probably explained by the fact that arterial CO_2 emboli are much better tolerated than air emboli because of the higher solubility of CO_2 in blood and tissues.

The small number of patients included in the study and control groups is not enough to draw any conclusive statement about CO_2-enriched surgical environment and VAE reduction. However, the main purpose of this preliminary study was to understand the feasibility of a new model of microenvironment in the surgical field to improve safety of the sitting position. There are evidences showing that the use of CO_2 can reduce the hemodynamic effects of VAE during surgery in the sitting position.

Conclusion

The sitting position in neurosurgery is still debated for the associated risks, in particular, venous air embolism. However, its utility is unequivocal. We tried to change the quality of the air composing the microatmosphere of the surgical field, in order to modify the composition of the air eventually entering the venous system. To this purpose, we replaced part of the preponderant nitrogen with CO_2 that excellently dissolves in human tissues. After setting the CO_2 delivery parameters in an experimental model, we measured a reduction of the hemodynamic effects of VAE in the clinical setting. Arterial CO_2 emboli are much better tolerated than air emboli due to the higher solubility of CO_2 in blood and tissues. Further studies including a larger amount of patients are required to confirm the real utility of CO_2 in neurosurgery.

Conflict of interest The authors declare that they have no competing interests.

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