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Case series

PULMONARY STRAIN AND END-EXPIRATORY LUNG VOLUME DURING APNEA TEST: A COMPARATIVE ANALYSIS USING ELECTRICAL IMPEDANCE TOMOGRAPHY

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Abstract

The apnea test, employed for brain death assessment, aims to demonstrate the absence of respiratory drive due to hypercapnia. The tracheal oxygen insufflation apnea test mode (I-AT) involves disconnecting the patient from invasive mechanical ventilation (iMV) for approximately 8 minutes while maintaining oxygenation. This test supports the diagnosis of brain death based on a specified increase in $PaCO_2$. Common complications include hypoxemia and hemodynamic instability, and lung collapse-induced reduction in end-expiratory lung volume (EELV).

In our case series utilizing electrical impedance tomography (EIT), we observed that continuous positive airway pressure during the apnea test (CPAP-AT) effectively mitigated lung collapse. This resulted in improved pulmonary strain compared to the disconnection of iMV. These findings suggest the potential benefits of routine CPAP-AT, particularly for potential lung donors, emphasizing the relevance of our study in providing quantitative insights into EELV loss and its association with pulmonary strain and potential lung injury.

Key words: electrical impedance tomography, brain death, apnea test, continuous positive pressure airway

Resumen

Stress pulmonar y volumen pulmonar de fin de espiración durante el test de apnea: Estudio comparativo utilizando tomografía por impedancia eléctrica

La prueba de apnea es una técnica diagnóstica ampliamente utilizada para la evaluación de la muerte cerebral, con el objetivo de demostrar la ausencia de impulso respiratorio debido a la hipercapnia. La variante de la prueba de apnea con insuflación de oxígeno traqueal (I-AT) implica desconectar al paciente de la ventilación mecánica invasiva (iVM) durante aproximadamente 8 minutos, manteniendo la oxigenación mediante un catéter de insuflación. Esta prueba respalda el diagnóstico de muerte cerebral cuando se determina un aumento de la $PaCO_2$ superior a 20 mmHg en comparación con el valor inicial o un nivel de $PaCO_2$ superior a 60 mmHg al final de la prueba. En nuestra serie de casos, la implementación de la tomografía de impedancia eléctrica (EIT) reveló que la prueba de apnea con presión positiva continua (CPAP-AT) mitiga eficazmente el colapso pulmonar. Este enfoque resulta en una mejora en la tensión pulmonar en comparación con la desconexión de iMV, demostrando su relevancia en el contexto de potenciales donantes de pulmones.

Palabras clave: tomografía por impedancia eléctrica, muerte encefálica, test de apnea, presión positiva continua en la vía aérea

The apnea test is a widely utilized diagnostic technique for brain death (BD) assessment, aiming to demonstrate the absence of respiratory drive due to hypercapnia[1]. The apnea test using the tracheal oxygen insufflation mode (I-AT) involves disconnecting the patient from invasive mechanical ventilation (iVM) for approximately 8 minutes while maintaining oxygenation by advancing an insufflation catheter into the endotracheal tube, to the level of the carina. This apnea test mode supports the diagnosis of BD when an increase in $PaCO_2$ exceeding 20 mmHg compared to the baseline or a $PaCO_2$ level exceeding 60 mmHg is determined at the end of the test.

Hypoxemia and hemodynamic instability are frequent side effects of the I-AT treatment that may be more severe in patients who already have hypoxemia or obesity[2, 3]. Another complication less reported during the I-AT is the magnitude of lung collapse induced by the loss of intrathoracic pressure. Additionally, lung collapse can persist after iVM reconnection, leading to reduced end-expiratory lung volume (EELV) and increasing pulmonary strain, even without hypoxemia[4]. Furthermore, a number of therapies, including recruitment maneuvers, may increase pulmonary strain and stress in an attempt to prevent this EELV loss, which could result in lung injury[5].

The CPAP-mode apnea test (CPAP-AT), an alternate technique, has shown better PaO_2/FiO_2 values than I-AT[6]. By maintaining constant pressure in the airway, CPAP-AT could prevent the occurrence of atelectrauma, thus mitigating the risk of lung injury in lung donors.

On the other hand, nothing is known about how lung volumes and lung strain behave in various apnea test modes.

Electrical impedance tomography (EIT) provides a valuable tool for assessing lung aeration by analyzing impedance (resistance to alternating current) in the thoracopulmonary system[7,8]. While this tool measures impedance variation, it maintains a linear relationship with volume changes, allowing these terms to be interchangeable. EIT can estimate the EELV during the apnea test[9]. Also can be measured the tidal volume and pulmonary strain, revealing potential mechanisms of lung injury with different ventilation strategies[10–12].

We provide a case series comprising three brain death diagnosis patients to examine differences in lung volumes and global pulmonary strain between I-AT and CPAP-AT. Because of their persistent oncological illnesses, these patients were not considered for organ donation.

Case series

The first case involved a 43-year-old female patient with a history of medical breast cancer, obesity (body mass index = 40.2), and asthma. She was diagnosed with BD attributed to a left frontotemporal intracerebral hematoma measuring 60 × 43 mm, accompanied by a midline shift of 13 mmHg. This condition was secondary to anticoagulation therapy for transverse venous sinus thrombosis.

The second case involved a 63-year-old female patient recently diagnosed with acute myeloid leukemia. She experienced refractory intracranial hypertension resulting from multiple intraparenchymal cerebral hematomas. These hematomas were a consequence of severe thrombocytopenia, a side effect of her ongoing chemotherapy regimen involving cytarabine and idarubicin.

In the third case, a 62-year-old female patient who had been recently diagnosed with adenocarcinoma affecting the pleura, heart, and bone, and whose primary tumor's origin remained unidentified, suffered an ischemic stroke in the right occipito-parietal region. This stroke was further complicated by extensive hemorrhagic transformation within the affected area.

In all three cases, the diagnosis of BD was confirmed by detecting systolic spikes in the examined arteries using transcranial Doppler ultrasound. The diagnostic process was completed by performing the apnea test.

We used EIT equipment to estimate lung volumes during the different apnea tests (Pulmovista V500, Drager, Germany). This equipment consists of a belt equipped with 16 channels and is positioned at the level of the fifth intercostal space. It allows continuous monitoring of global and regional changes in TV and EELV.

Initially, all patients underwent I-AT. Unfortunately, one patient experienced hypoxemia and had to discontinue the test prematurely. However, the remaining patients completed the study without any complications. Throughout the apnea period for all patients, EIT consistently showed the complete cessation of pulmonary ventilation. During I-AT, there was a notable decrease in EELV for the three patients. Specifically, in patient 1, EELV decreased by 701 ml; in patient 2, 669 ml; and in patient 3, 433 ml. This reduction in EELV indicates lung collapse resulting from the cessation of intrathoracic positive pressure.

During the CPAP-AT, we observed minor reduction in EELV compared to I-AT. Specifically, in patient 1, EELV decreased by 282 ml; in patient 2, by 97 ml; and in patient 3, by 146 ml. This indicates that the applying continuous positive pressure during the apnea test effectively prevented a substantial decrease in EELV compared to I-AT. It prevented of approximately 59.8%, 85.5%, and 66.3% of the EELV reduction observed during I-AT.

Since the tidal volume was constant, the lower reduction in EELV after CPAP-AT implied an improvement in pulmonary strain compared to I-AT. In CPAP-AT, the pulmonary strain values were 0.88, 0.76, and 0.80, while in I-AT, they were 0.91, 1.20, and 1.07 for patients 1, 2, and 3, respectively. Table 1 provides comprehensive information about the demographic characteristics, ventilatory parameters, and EIT data for the three patients involved in the study. For a visual representation of these changes, please refer to Figure 1, which illustrates the variations in tidal impedance and end-expiratory lung impedance during I-AT and CPAP-AT.

Written informed consent was obtained from patient's relatives.

Discussion

In this case series of three patients assessed using EIT, it was observed that CPAP-AT effectively mitigated the lung collapse that occurs when disconnecting from iMV during I-AT. This prevention resulted in preserving 70.5% (+/-11) of EELV. Since tidal volume remained constant during both tests, the more significant decrease in EELV during I-AT increased pulmonary strain in all three patients compared to CPAP-AT.

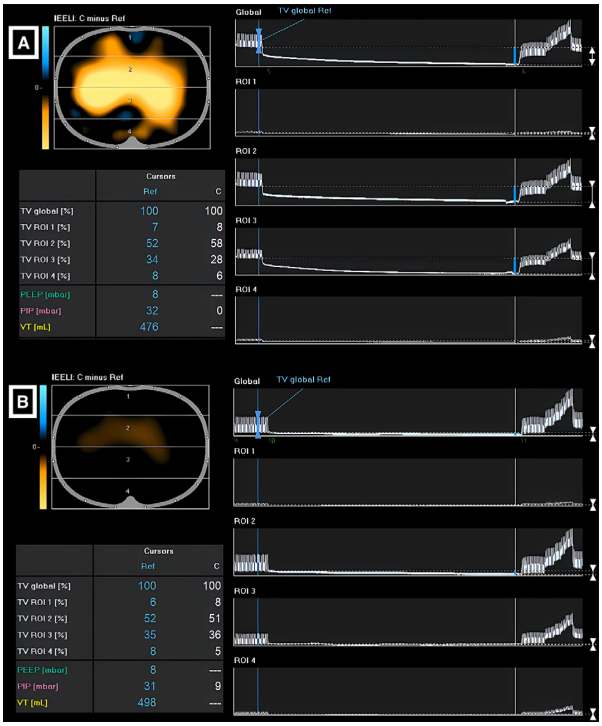
Pulmonary strain is defined as the relation between tidal volume and residual functional capacity (VT/FRC) and reflects the deformation

Table 1 | Demographic characteristics, ventilatory parameters, and electrical impedance tomography data

	Patient 1	Patient 2	Patient 3
Demographics characteristics			
Sex	Female	Female	Female
Age (years)	44	63	62
BMI (kg/m^2)	40	32.4	26.2
Ventilatory parameters			
Theoretical weight (kg)	58.4	54.3	65.1
Tidal volume (ml)	500	498	540
mL/kg predicted body weight	8.5	9.1	8.3
PEEP (cmH_2O)	10	8	6
Respiratory rate (rpm)	18	20	15
EIT parameters			
EELV lossI-AT (ml)	701	669	433
EELV lossCPAP-AT (ml)	282	97	146
Prevented EELV loss*I-AT (%)	419	572	287
Prevented EELV loss*CPAP-AT (%)	59.8	85.5	66.3
Pulmonary strainI-AT	0.91	1.20	1.07
Pulmonary strainCPAP-AT	0.88	0.76	0.80

I-AT: apnea test through tracheal oxygen insufflation; CPAP-AT: apnea test in continuous positive airway pressure mode; BMI: body mass index; BD: brain death; EELV: end-expiratory lung volume
** Prevented EELV loss: Represents the difference in EELV volume lost during I-AT and the volume of EELV lost in CPAP-AT*
Pulmonary strain is defined as the relation between Impedance tidal variation and end expiratory lung impedance (TV/EELI)

Figure 1 |Monitoring of tidal impedance variation and end-expiratory lung impedance using electrical impedance tomography during the apnea test with tracheal oxygen insufflation and during the application of continuous airway pressure



Impedance changes are represented globally and according to regions of interest (ROI) for analysis.
ROI 1 corresponds to ventral regions
ROI 2 corresponds to central ventral regions
ROI 3 corresponds to central dorsal regions
ROI 4 corresponds to dorsal regions
In the upper left quadrants, a cross-sectional representation illustrates the loss of EELI at the end of each test relative to the beginning. A greater loss of EELI is indicated by a higher intensity of orange color

that the alveolar surface undergoes during inspiration and expiration[4]. In several situations, such as acute respiratory distress syndrome (ARDS), an increase in pulmonary strain is associated with lung injury[4, 13]. Gogniat et al. demonstrated in an experimental model of ARDS that pulmonary strain can be measured by EIT[14]. Therefore, the presence of an elevated pulmonary strain at the end of I-AT could indicate potential lung injury due to lung collapse compared to CPAP-AT, even in the absence of hypoxemia. Furthermore, this intervention enabled one of the patients to complete the test, unlike the I-AT mode, where the test had to be suspended due to hypoxemia.

At present, the I-AT method remains the most commonly employed test in the diagnosis of brain death. However, it is associated with potential complications, including hypoxemia, which can be attributed to multiple factors, such as the reduction in airway pressure causing lung collapse. Solek-Pastuszka et al. conducted a study demonstrating that CPAP-AT effectively prevents a drop in PaO_2/FiO_2 compared to I-AT, regardless of whether patients are hypoxemic [6]. This observed benefit aligns with our findings, where using CPAP-AT effectively safeguards against the decrease in EELV. These findings are particularly relevant for potential lung donors, as the use of I-AT may potentially lead to increased pulmonary strain[15,16]. Therefore, it may be prudent to consider routine CPAP-AT for this subgroup of patients.

In our case series, the application of EIT produced results consistent with those reported by Westphal et al. where EELV remained stable during CPAP-AT. In contrast, in the case of I-AT, it exhibited a gradual decline[9]. An innovative aspect of our study is quantifying the estimated loss of EELV and its relationship with the increase in pulmonary strain and potential lung injury. Furthermore, to our knowledge, this is the first study utilizing EIT to assess pulmonary strain generated during the apnea test in two different modalities.

Finally, continuous monitoring of tidal ventilation using EIT revealed the absence of ventilatory movements during the apnea test. This situation could lead to confusion in standard clinical practice, as cardiac movements may be mistakenly interpreted as ventilatory movements. In this scenario, EIT monitoring displayed minimal impedance variations, primarily reflecting intrathoracic impedance changes from cardiac volume fluctuations during systole and diastole.

In conclusion, within this patient series, using EIT revealed that employing CPAP during the apnea test effectively mitigated lung collapse and improved pulmonary strain compared to the disconnection of iMV.

Conflict of interest: None to declare

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