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Original article

The Carbon Dioxide Flushing Technique: A Novel Approach Using Oxygen Measurements to Evaluate the Elimination of Room Air from Thoracic Stent-Grafts

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Abstract

Background: The study evaluates a novel technique using oxygen measurements to indirectly evaluate the behavior of carbon dioxide (CO_2) in the residual gas released by thoracic stent-grafts and to better understand the mechanism of the CO_2 flushing technique. ***Methods:*** Ten Zenith TX2 ProForm thoracic stent-grafts (ZDEG-PT-34-199-PF, Cook Medical, Bjæverskov, Denmark) were equally divided into 2 groups (Group A and B). Group A was flushed with 60 ml of 0.9% saline. Group B was flushed with 100% carbon dioxide gas followed by 60 ml of 0.9% saline. The stent-grafts were deployed into a plastic tube that was placed and fixated to the bottom of a translucent container filled with water to collect the residual air released by the stent-grafts. Oxygen (O_2) concentration and gas volume were measured in the released gas. ***Results:*** The oxygen concentration was significant ($p<0.001$) lower after additional carbon dioxide flush compared to standard flush (18.5% vs 19.6%). Furthermore, the absolute oxygen volume was significantly lower after additional carbon dioxide flush than without (0.18 ml vs 0.32 ml, $p=0.041$). The total amount of released gas appeared lower with carbon dioxide flush than without (0.98 ml vs 1.65 ml, $P=0.058$). ***Conclusions:*** CO_2 absorption into saline and replacement of room air by CO_2 inside the stent-graft may lead to a reduction of released gas during stent-graft deployment in an experimental setting.

Keywords: ***air embolism, aortic aneurysm, carbon dioxide, stroke, thoracic endovascular aortic repair***

Introduction

Thoracic endovascular aortic repair (TEVAR) is the treatment of choice for descending aortic pathologies but endovascular treatment strategies are also more and more applied at the level of the ascending aorta and aortic arch [1-4]. Stroke remains one of the major drawbacks of TEVAR and silent brain infarctions (SBI) are of concern as those can be associated with cognitive function loss during follow-up [5,6]. Clinically apparent strokes are reported in 2.3% to 8.2% for standard TEVAR and up to 26% for endovascular aortic arch repair [7]. Recent studies showed that the rate of SBI after TEVAR is even higher and present in 50% - 80% of patients [8,9] what can be associated with neurocognitive decline in the long term. Release of air from the stent-graft system has been documented after standard flushing and is discussed as one of the reasons for cerebral embolism [10,11]. Significant reduction of the released air can be achieved by adding CO_2 to the standard flushing protocol [12]. But the exact mechanism of the volume reduction as well as the amount of room air that can be exchanged by CO_2-flushing is not known. This is complicated by the fact, that direct measurements of the CO_2 concentration in small amounts of gas released by the graft is not easily possible. Still there is no CO_2 probe available. This study evaluates a novel technique using oxygen measurements to indirectly evaluate the behavior of CO_2 in the residual gas released by thoracic stent-grafts and to better understand the mechanism of the CO_2 flushing technique.

Materials and Methods

Study Design

In an experimental set-up ten similar thoracic stent-grafts were divided into 2 groups of 5 stent-grafts each (Group A and B). The five stent-grafts in group A (A1-A5) were flushed with 60 ml of 0.9% saline. The five stent-grafts of group B (B1-B5) were flushed with 100% carbon dioxide gas applied with a pressure of 1,2 bar for 5 minutes followed by 60 ml of 0.9% saline. The flush was done through the side port of the flushing chamber. After flushing, all stent-grafts rested for 10 minutes flat on the bench ahead of deployment with the aim to simulate the real situation in the operation room. Comparison was made between the two groups of grafts in aspect to total released gas volume and oxygen concentration, as well as to the amount of oxygen calculated from the oxygen concentration of each sample volume.

According to the experimental set-up from previous publications the stent-grafts were deployed into a plastic tube that was placed and fixated to the bottom of a translucent container filled with water to collect the residual air released by the stent-grafts [12]. As a modification to the measurement system an electrochemical oxygen sensor (O_2 Microsensor OX-500-007533, flowcell, glass, UNISENSE, Denmark) was integrated (Fig. A and B). Ahead of collecting the gas into the volume measurement syringes, it was exposed to the sensor for a minimum of 30 seconds to measure the oxygen concentration avoiding room air contamination in a glass-tubing. After the oxygen measurement, the complete gas was aspirated and quantified using the syringe technique allowing measurements of small gas volumes down to 0.02 ml.

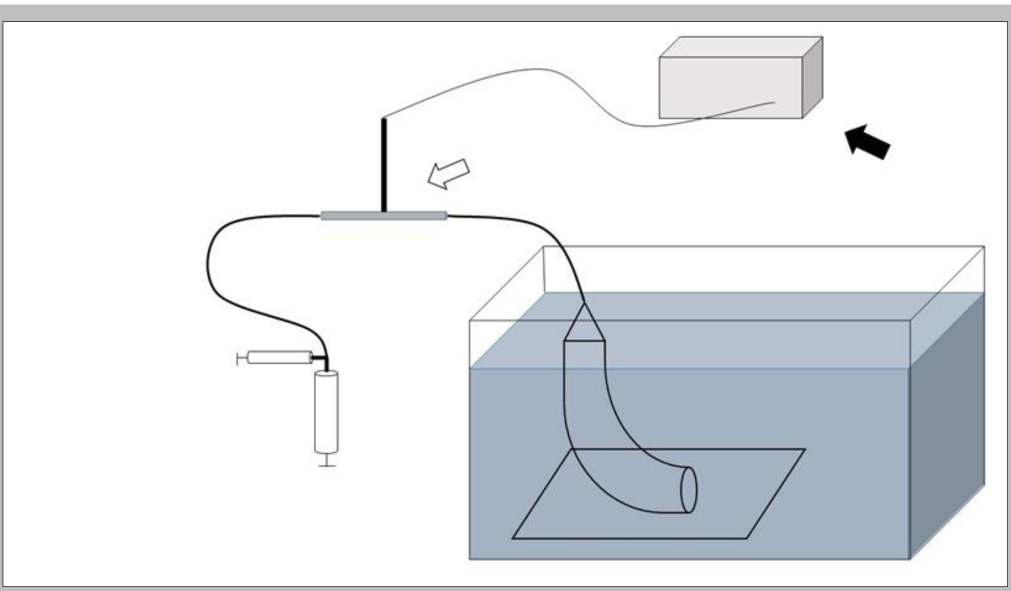

Figure 1: Draft of the Experimental setup. The stents were deployed into the curved plastic pipe (50 mm diameter) and the released air was collected in the tip of the pipe. The UNISENSE oxygen sensor (white arrow) was integrated into the tubing and connected to the tip of the pipe. After deploying the stent-graft, the released gas was aspirated into the tubing, presented to the sensor to measure the concentration of oxygen and finally collected into the syringes to quantify the volume. The sensor itself was connected to the UNISENSE Amplifier (black arrow).

Figure 2: Oxygen sensor. The oxygen sensor (O_2 Microsensor OX-500-007533, flowcell, glass, UNISENSE, Denmark) has a “T-shape”. The glass tube on the one end of the sensor was integrated into the tubing of the experimental setup. The wire on the other end of the sensor is connected with the UNISENSE amplifier.

Stent-grafts

Ten equal Zenith TX2 ProForm thoracic stent-grafts (ZDEG-PT-34-199-PF, Cook Medical, Bjæverskov, Denmark) loaded on a Z-Trak Plus introducer system with a 20F hydrophilic sheath were used. The stent-grafts are equipped with a flushing chamber with a side port and a captor valve [12]. The central cannula wire and the peel-away sheath were removed to prepare the stent-grafts for flushing.

Oxygen-sensor and analysis software

The electrochemical sensor was connected to an amplifier (O_2 UniAmp, UNISENSE, Denmark) which was connected to a computer and the data was displayed using a dedicated analysis software (SensorTrance logger, UNISENSE, Denmark).

The principle of the oxygen microsensor is based on diffusion of oxygen through the sensor tip membrane to an oxygen reducing cathode. The reducing cathode is polarized against an internal Ag/AgCl anode. The resulting sensor signal is in the picoampere (pA) range and is measured by the Amplifier (O_2 UniAmp, UNISENSE, Denmark). The amplifier signal is converted to an output signal in millivolt (mV).

The oxygen sensor needs to be calibrated. As the oxygen sensor responds linearly to changes in oxygen concentrations a twopoint calibration is sufficient. Therefore, we used an anoxic solution (HI7040-2, Zero Oxygen Solution, HANNA instruments, Vöhringen, Germany) and 100% oxygen (according to the IFU of UNISENSE).

Knowing the mV values of the sensor at 0% oxygen and 100% oxygen the oxygen concentration for each gas sample could be calculated.

Data analysis

Independent two sample t-tests were used for normally distributed continuous variables. The threshold of statistical significance was $p<0.05$. The statistical analysis was done with SPSS for Macintosh (IBM, Version 27).

Results

Table 1 shows the amounts of released total gas during deployment, the oxygen concentration and the absolute volume of oxygen in the released gas. The oxygen concentration was significant ($p<0.001$) lower with carbon dioxide flush than with standard flush (18.5% vs 19.6%). Furthermore, the absolute oxygen volume was significantly lower with carbon dioxide flush than without (0.18 ml vs 0.32 ml, $p=0.041$). The total amount of released gas appeared lower with carbon dioxide flush than without (0.98 ml vs 1.65 ml, $P=0.058$).

Table 1: total volumes of released gas during deployment, the oxygen concentration and the calculated total volume of oxygen.

	total volumes of released gas in ml		**oxygen concentration in the volume samples in %**		**calculated total volume of oxygen in ml**	
Stentgraftnumber	**Group A saline flush**	**Group B CO_2 + saline flush**	**Group A saline flush**	**Group B CO_2 + saline flush**	**Group A saline flush**	**Group B CO_2 + saline flush**
1	1.35	1.6	19.61	18.80	0.26	0.30
2	1.8	0.8	19.05	18.33	0.35	0.15
3	1.9	0.75	19.81	18.58	0.37	0.14
4	2.2	1.35	19.91	18.43	0.43	0.25
5	1	0.4	19.38	18.47	0.20	0.07
mean	1,65	0,98	19.56	18.52	0.32	0.18
P =	0.058		<0.001		0.041	

Discussion

This study introduces an electrochemical method using oxygen concentration measurements to indirectly calculate the influence of carbon dioxide while flushing thoracic stent-grafts. The results show, that flushing with carbon dioxide significantly reduces the concentration and the amount of oxygen in the gas volume released by the graft. In addition, the total amount of released gas from the stent-graft after CO_2 flush appears to be lower, although in this experiment just marginally significant (0.98 ml vs 1.65 ml, $p = 0.058$), this is in line with results of previous experiments with larger groups of grafts [12].

The mechanism of the CO_2 flushing technique is yet not fully understood and the lack of tools for direct CO_2 measurements in small volumes while avoiding room air contamination does complicate the analysis of CO_2 behavior while flushing the stent-grafts. By measuring oxygen as a known compound of room air and based on the physical characteristics of CO_2 that is more soluble in blood than nitrogen or oxygen, indirect conclusions on the CO_2 behavior appear possible.

To explain the lower oxygen concentration (18.5%% vs 19.6%, $p < 0.001$) and total volume (0.18 ml vs 0.32 ml, $p=0.041$) in group B compared to group A, we assume that CO_2 replaces room air, which is present in the stentgraft, and then absorbed into the saline during saline-flushing and resting time. This is indicated by the reduced total gas volumes in group B and the lower O_2 concentration and supports the hypothesis, that CO_2 helps to replace room air by a less harmful gas in TEVAR.

Since its introduction, the CO_2 flushing technique has become a standard of stentgraft preparations and is associated with a lower rate of SBI after procedures involving the aortic arch and thoracic aorta in some European centers [8]. CO_2 is easily available out of CO_2-cylinders in the operating room. Although our results help to understand the beneficial impact of the CO_2 flushing technique, the indirect O_2 measurement is a clear limitation of the set up. Furthermore, the stent-grafts used for this study were previously deployed and reloaded, limiting the validity of measured gas volumes and its comparability to a real intraoperative scenario. However, the general principle of air-replacement by CO_2 and the absorption of CO_2 into saline might apply to a similar extend to the lower gas-volumes usually measured in unused stent-grafts.

Conclusions

This experiment introduces electrochemical oxygen measurements to investigate the mechanism of the CO_2 flushing technique indirectly. Replacement of room air by CO_2 inside the stent-graft as well as CO_2 absorption into saline induce a reduction of released gas during stent-graft deployment in an experimental setting.

Ethics approval and consent to participate

Not applicable

List of abbreviations

CO_2: carbon dioxide
TEVAR: Thoracic endovascular aortic repair
SBI: silent brain infarctions
pA: picoampere
mV: millivolt

Conflicts of Interest

Tilo Kölbel acts as a proctor for and has intellectual property with Cook Medical. He also receives travel and research grants from Cook Medical. Cook Medical provided equipment and stent grafts.

Funding Statement

None

Authors' contributions

Kugarajah Arulrajah, Tilo Kölbel, Thomas Gandet, Giuseppe Panuccio and Fiona Rohlffs contributed to the literature search; Kugarajah Arulrajah, Tilo Kölbel, Thomas Gandet and Fiona Rohlffs contributed to the study design and data collection and analysis; Kugarajah Arulrajah and Fiona Rohlffs contributed to the writing; Kugarajah Arulrajah, Tilo Kölbel and Fiona Rohlffs contributed to the critical revision; Kugarajah Arulrajah., Tilo Kölbel, Thomas Gandet, Giuseppe Panuccio and Fiona Rohlffs contributed to the final approval of the study.

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