Direct visualization of carbon dioxide field flooding: Optical and concentration level comparison of diffusor effectiveness

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ABSTRACT

Objective: Carbon dioxide field flooding during open-heart surgery is intended to avoid blood-air contact, bubble formation, and embolism, and therefore potential neurologic and other ischemic complications. The inert gas is invisible, and thus its use and effectiveness are heavily debated. We intended to provide better insight in the behavior of the gas via direct concentration measurements and visualization of the gas cloud.

Methods: A transparent rectangular model of the open thorax was created, foreseen with carbon dioxide concentration sensors in 2 locations (atrial and aortic incisions), and placed in an optical test bench that amplifies the diffraction gradients. Six different commonly used carbon dioxide diffusors (3 commercial, 3 improvised) were tested with different flow rates of gas delivery (1, 4, 7, 10 standard liter per minute [SLPM]) and combined with the application of suction.

Results: The imaging reveals that commercially available diffusors generally create less turbulent flow than improvised diffusors, which is supported by the concentration measurements where improvised diffusors cannot generate a 100% carbon dioxide atmosphere at the aorta incision location. The atrial incision is easier to protect: 0% air with all commercial devices for all flow rates greater than 1 SLPM. A flow rate of 1 SLPM does not create an inert atmosphere with any device.

Conclusions: The optically observed carbon dioxide atmosphere is unstable and influenced by many factors. The device used for diffusion and the flow rate are important determinants of the maximum gas concentration that can be achieved, as is the location where this is measured. (*J Thorac Cardiovasc Surg* 2020;159:958-68)

CO₂ flow at 10 SLPM from an improvised delivery tube (L) versus a commercial diffusor (R).

Central Message

CO₂ field flooding is not well understood. We provided insight in diffusor effectiveness via visualization and concentration measurements and demonstrated an unstable CO₂ atmosphere.

Perspective

Many misunderstandings exist about CO₂ field flooding, mainly because the gas cannot be observed. This engineering study literally reveals the gas behavior, and the observations are corroborated by instantaneous concentration measurements. The reported findings should be mostly of interest to cardiac surgeons, who can easily improve cerebral protection of their next patient.

See Commentaries on pages 969 and 970.

Blood circulation is a closed system shielded from the extracorporeal environment. During open or major vascular surgery, atmospheric air can freely enter and form air bubbles in the blood, which after removal of the clamps or re-commencing circulation may be driven toward the brain and cause neurologic damage.¹ This is caused not only by the blockage of an artery itself (even a 2.5- μ L bubble can

disrupt brain function in less than 30 seconds²) but also by the an inflammatory response. In addition to stroke as the most feared outcome, another complication that may be caused by air embolism is silent infarction and its potential for postoperative cognitive disorders,³⁻⁵ for which no clear diagnostic and measurable outcomes are available.

Therefore, it is an important part of a cardiac surgery procedure to carefully remove air bubbles from the blood before liberating heart and vessels (deairing). The

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Abbreviations and Acronyms

- CO₂ = carbon dioxide
- IQR = interquartile range
- SLPM = standard liter per minute

traditional surgical methods, such as vent catheters, aspirating with needles, shaking the heart, or tilting the operating table during pulmonary expansion, only remove a portion of the entrapped air, as is repeatedly proven with intraoperative transesophageal echography.^{6,7}

The approach to create an inert atmosphere in the thorax with carbon dioxide (CO₂) appears to be more safe and consistent, but has been a source of controversy ever since its inception in the late 1950s.⁸ The concept is well known: because CO₂ is approximately 70% heavier (density at standard temperature and pressure: 1.98 kg/m³) than air, the gas will fill the thorax cavity and push the air up and away from the blood. CO₂ easily dissolves in blood (solubility is 25× that of air) and does not have the risk

of blocking a vessel long enough to cause ischemic damage. But CO₂ is also an invisible gas, and thus it cannot be observed if it effectively fills the thorax, which quantities need to be applied, how long it stays present in the thorax, and how dangerous it could be for the surgical staff.

Despite the long history of CO₂ field flooding, relatively few scientific studies (barely 300^{9,10}) have been performed, with inconclusive results,^{11,12} and the ongoing debate about the effectiveness causes a divide between proponents¹³⁻¹⁶ and opponents^{17,18} of this method. Surgeons who are convinced that CO₂ forms a protective atmosphere to prevent or reduce blood-air contact may still use it in an ineffective way because of the lack of understanding of the gas behavior. The resulting inconsistent application of CO₂ makes it difficult to prove or disprove the effectiveness of CO₂ field flooding in clinical trials.

The last 15 years have seen a renewed interest in assessing the effectiveness of CO₂ field flooding, due in part to improved ultrasound technology to assess the embolic load.^{6,7,19} With the development of the first commercial CO₂ diffuser, a range of laboratory studies were performed that demonstrated that flow rate, presence of

FIGURE 1. Top: Color-coded photographs of the 6 different diffusers that were tested in the thorax model. Bottom: sketch of the test setup consisting of a box representing the open thorax and indicating the locations of the diffuser under test, the suction tip, and the high-speed CO₂ concentration sensors. The green arrows indicate the flow of CO₂ gas into the model, and the brown arrow indicates the gas evacuation via the suction tip that was used in parts of the protocol (Table 1). CO₂, Carbon dioxide.

suction, and design of the diffuser make a notable difference in the remaining air content in the thorax.²⁰

In this article, we aim to contribute to the better understanding of CO₂ field flooding via direct visualization of the gas mixing, combined with high-speed measurements of the CO₂ concentration directly inside a thorax model.

MATERIAL AND METHODS

Setup

A simplified model of the open thorax was created as a rectangular box with 18-cm length and 10-cm width and height and airtight seals (Figure 1). Two opposing panels were made from 2-mm thick acrylic to enable visualization as a long-axis projection. In 1 of the side panels, 2 high-speed, wide range (0%-100%) CO₂ sensors were installed (Gas Sensing Solutions Ltd, Cumbernald, UK): a Cozir (2 Hz) in cranial mid-height position (simulating the position of the left atrium) and a SprintIR (20 Hz) in a central anterior (top-height) position (simulating the anatomic position of the ascending aorta). The sensors were calibrated before each measurement set with medical grade CO₂ gas.

Six different CO₂ diffusers were subsequently installed in the most cranial position of the model and connected to a CO₂ tank via a regulator and digital gas flow meter (Massview, Bronkhorst High-Tech b.v., Ruurlo, The Netherlands). The flow meter was calibrated for CO₂ in standard liter per minute (SLPM); a volumetric flow rate scaled to standard temperature and pressure (0°C, 1 bar), which enables comparison of gas flows under pressure.

The model and instrumentation were placed in a Z-type Schlieren setup with 2 150-mm spherical mirrors, with the following components all installed on XYZ-micrometer stages for precise alignment and focusing: a point light source, a knife blade, and a CCD camera (AC1920, Basler AG, Ahrensburg, Germany). The Schlieren technique amplifies the small diffraction gradient between CO₂ and air. Figure 2 shows that with the naked eye, no gas can be observed coming out of the diffuser, while simultaneously the video camera (see TV monitor) captures the Schlieren effect and clearly shows the CO₂ gas flow. Isolated images of the Schlieren effect are displayed in Figure 3. The boundary between CO₂ gas and air is indicated by shadows that cast a 3-dimensional effect.

Diffusers

Three commercially available CO₂ diffusers were tested:

- CarbonAid (CardiaInnovation AB, Kungens Kurva, Sweden)
- CarbonMini (CardiaInnovation AB)
- Temed Gas Diffusor (Temed, Sidlesham, United Kingdom).

These were compared with 3 improvisations that are frequently seen in cardiac surgery:

- multi-perforated drainage catheter (Drenofast; Iberhospitex SA, Barcelona, Spain),
- a 1/8" × 1 × 16" polyvinyl chloride tube
- a 1/8" × 1/16" polyvinyl chloride tube covered with 3 layers of gauze.

These are further referred to as "drainage," "tube," and "gauze," respectively.

Protocol

Video data were recorded with the optical system while CO₂ concentration data were digitally acquired from the CO₂ sensors. An overview of the performed measurements, split in experiments A and B, is presented in Table 1. Table 1 was replicated 3 times at different dates, and in between, the setup was completely rebuilt. For experiment A, all 6 diffusers were sequentially tested while aligned with the vertical axis, and at 4 different

FIGURE 2. Illustration of the suitability of the Schlieren principle for the study of CO₂ field-flooding: CO₂ gas coming from a gas diffuser at 4 SLPM cannot be observed with the naked eye (red circle, direct photographer's view), while simultaneously an obvious gas cloud can be seen on the LCD screen, which comes from a live-view camera aiming at the setup's spherical mirrors.

flow rates (1, 4, 7, or 10 SLPM), without the use of suction. In experiment B, only the 3 commercial diffusers were tested under different conditions: a second data set with the diffuser tilted 45° in the medial plane and a third data set in the standard vertical orientation but combined with the application of suction. For this, a suction tip was installed vertically at the caudal side of the model, and a regulated suction flow of 5 L/min was imposed.

Before each measurement, the CO₂ tank was opened, and the regulator modified to read the desired gas flow (1, 4, 7, or 10 SLPM). The CO₂ delivery tube was then clamped, and the thorax model emptied via suction until both sensors indicated less than 1% CO₂ concentration. Recording was started, and the clamp was removed to immediately deliver the CO₂ gas at the desired flow rate. This was maintained until the CO₂ concentration reached a plateau.

Data Processing

A custom algorithm written in MATLAB software (MathWorks Inc, Natick, Mass) detected the concentration plateau from each concentration measurement file. Two continuous quantitative variables were extracted from the plateau (Figure 4): the maximum CO₂ concentration that was achieved (ie, the average of the plateau) and the time to reach the plateau (rise time). The data are graphically presented as Tukey box plots and reported in the text as median and interquartile range (IQR). STATA software

FIGURE 3. Demonstration of gas clouds generated by a Temed CO₂ diffuser at different flow rates (1, 4, 7, or 10 SLPM). The black vertical rod on the right side of the diffuser is the shadow of the caudally placed suction tip, which was not sucking during these recordings. *SLPM*, Standard liter per minute.

(StataCorp LLC, College Station, Tex) was used to fit multi-level, mixed-effects models to the data of each experiment, with the covariate “device” defined as random effect. Fixed factors were “position” and “flow rate” (experiment A), and “suction” for experiment B (tilting was excluded after an initial screening). A Bonferroni correction of the *P* levels was applied for subsequent pairwise comparisons.

TABLE 1. Overview of the test protocol

Experiment A							
Diffusor		CO ₂ flow rate		Condition		No. of runs	Replications
CarbonAid	Commercial	1/4/7/10 SLPM		Vertical		24	3
CarbonMini							
Temed							
Drainage catheter							
Tube	Improvised						
Tube + gauze							
Experiment B							
Diffusor		CO ₂ flow rate		Condition		No. of runs	Replications
CarbonAid	commercial	1/4/7/10 SLPM	Vertical	45° oblique	Vertical + suction	36	3
CarbonMini							
Temed							

CO₂, Carbon dioxide; *SLPM*, standard liter per minute.

FIGURE 4. Comparison of 2 commercial gas diffusers and the effect of gas delivery flow rates (1, 4, 7, or 10 SLPM) on the maximum achievable gas concentration in the thorax and the rise time needed to achieve this. The right side of each graph (>100 seconds) illustrates how rapidly gas concentration decays when delivery is cut off. These data were obtained from a CO₂ concentration sensor in position 2 in the thorax model (simulation of aorta incision) and without application of suction from a blood sucker. CO₂, Carbon dioxide; SLPM, standard liter per minute.

RESULTS

Experiment A

The optical results for experiment A, obtained with the Schlieren system, are presented in [Videos 1 to 4](#). Each video concentrates on a specific flow rate and shows parallel frames with the 6 tested devices in the thorax model. The shadow of the diffuser and the suction tip are visible in the frames, although suction was not active during these specific recordings. At the start of gas flow, each video shows outspoken gas clouds, where some devices show high turbulent mixing of CO₂ and air, while the CarbonAid device generates a distinctive laminar downflow. Especially with this device, as the thorax keeps filling, the boundary between the gases fades, indicating that the model is completely filled with CO₂. While [Videos 1 to 4](#) enable comparison of devices at a single flow rate, [Figure 3](#) shows the comparison of different flow rates for 1 device, namely,

the Temed diffuser. It also shows that for this device, higher flow rates generate more drastic turbulent mixing.

When comparing [Video 1](#) (at 1 SLPM) with [Videos 2 to 5](#), or likewise comparing the different panels of [Figure 3](#), it can be observed that at higher flow rates the CO₂ gas flows over the edge of the thorax model, but at 1 SLPM it does not. Also the time-varying CO₂ concentration depicted in [Figure 4](#) for the Temed and CarbonAid diffusers reveals a big discrepancy between a 1 SLPM flow rate and the other flow rates. The maximum achievable concentration of CO₂ in the thorax model is well below 100% at the aortic incision level if 1 SLPM is used, and it also takes longer to reach a steady state. This is further confirmed in [Figure 5](#), in which a comparison of the maximum achieved CO₂ concentration (top) reveals notably lower concentrations for the 1 SLPM flow rate of CarbonAid, CarbonMini, Temed, and Gauze compared with the higher flow rates. The mixed model (r^2 : 0.96) shows a significant effect of device, flow rate, position, and the device*flow rate interaction. The Bonferroni pairwise comparison of all devices further reveals that Drainage and Tube generate significantly lower CO₂ concentrations than all other devices over all factors, whereas concentrations present at the aorta incision are also significantly lower than at the atrial position. A pairwise comparison of the different devices is presented in [Table 2](#).

The lower panel of [Figure 4](#) also shows that the maximum CO₂ concentration achieved with a Temed diffuser at 10 SLPM is actually lower than at 4 and 7 SLPM, indicating that a higher flow rate does not necessarily lead to a higher concentration. Similar trends can be seen in [Figure 5](#), where the Temed, simple tube, and tube with gauze all show decreasing CO₂ concentrations for increasing flow rates. It appears that each device has an optimal flow rate, which is for instance 1 SLPM for the drainage catheter, and 4 SLPM for Temed and Gauze. In general, for all flow rates and both positions, the commercial Temed and the improvised Gauze show a good agreement in performance, and no significant differences were found between these devices. The CarbonAid is the only device that achieves a 100% CO₂ atmosphere for all flow rates (except 1 SLPM) in all positions. At the highest flow rate of 10 SLPM, it is significantly more effective than all other devices. The least effective device at these flow rates is the multi-perforated drainage catheter, which still allows/entrains approximately 80% of air into the thorax and is thereby significantly worse than all other devices. In [Video 3](#) or the “drainage” section of [Figure 6](#), the drainage catheter shows extraordinary gas delivery in the form of a massive cloud of small turbulences that rises high above the thorax model, while other devices generate less turbulent clouds where the gas gently flows over the model edges.

The rise time is significantly higher at 1 SLPM versus the other flow rates over all factors, whereas there is no

VIDEO 1. All tested diffusers are shown side by side, dispersing CO₂ in the rectangular thorax model at a flow rate of 1 SLPM. Video available at: [https://www.jtcvs.org/article/S0022-5223\(19\)30936-5/fulltext](https://www.jtcvs.org/article/S0022-5223(19)30936-5/fulltext).

significant contribution of the position to the fitted mixed effects model (r^2 : 0.90). At 1 SLPM, it takes approximately 3 minutes to fill the thorax with a steady atmosphere of CO₂, whereas at other flow rates it takes only 1 minute. It appears that at the highest flow rates (4, 7, or 10 SLPM), particularly in position 2, the drainage catheter stands out positively for reaching its steady-state plateau faster than the other devices: a median rise time of 26 seconds (IQR, 14) for the drainage catheter (at 4 SLPM; position 2) versus 71 seconds (IQR, 16) for all the other devices combined. However, it needs to be considered that this catheter has a lower plateau: 16% CO₂ (IQR, 7.5) versus 94% (IQR, 6.5) by the other devices for the same condition, and is thus far worse at creating a protective CO₂ environment. Overall, every factor introduced in the multilevel model had a statistically significant impact on maximum CO₂ concentration and rise time, with the exception of “position,” which had no significant effect on rise time. The rise time could be considered an indicator of how quickly the CO₂ atmosphere could recover to its original composition after it has been disturbed, for instance by surgical maneuvers.

VIDEO 3. All tested diffusers are shown side by side, dispersing CO₂ in the rectangular thorax model at a flow rate of 7 SLPM. Video available at: [https://www.jtcvs.org/article/S0022-5223\(19\)30936-5/fulltext](https://www.jtcvs.org/article/S0022-5223(19)30936-5/fulltext).

Experiment B

Figure 7 shows that a suction of 5 L/min has a negative effect on the generation of a CO₂ atmosphere and reduces the maximum achievable concentration to the effect that no device at any of the tested flow rates was able to generate a consistent 100% CO₂ reading in the “aorta incision” position. For the “atrium incision” region, only CarbonAid and CarbonMini could achieve a consistent 100% reading (IQR <3) with 7 and 10 SLPM flow rates. The mixed effects model (r^2 : 0.93) confirms that suction has a significant impact on the maximum CO₂ concentration. The pairwise comparison further shows that also with suction, the lowest flow rate performs significantly worse than the other flow rates: CO₂ values do not exceed 20% at 1 SLPM anywhere in the thorax model, whereas with 4 SLPM it is already possible to reach 90% in the “atrium incision.” Overall, the CarbonAid device performs better than the other devices when suction is applied, but the difference with other devices is most notable in the “aortic incision.” In contrast with the effect of suction, a tilted orientation of the diffuser, has no effect on the Max CO₂ concentration or rise time for

VIDEO 2. All tested diffusers are shown side by side, dispersing CO₂ in the rectangular thorax model at a flow rate of 4 SLPM. Video available at: [https://www.jtcvs.org/article/S0022-5223\(19\)30936-5/fulltext](https://www.jtcvs.org/article/S0022-5223(19)30936-5/fulltext).

VIDEO 4. All tested diffusers are shown side by side, dispersing CO₂ in the rectangular thorax model at a flow rate of 10 SLPM. Video available at: [https://www.jtcvs.org/article/S0022-5223\(19\)30936-5/fulltext](https://www.jtcvs.org/article/S0022-5223(19)30936-5/fulltext).

VIDEO 5. Three scenes with a sequence of disturbances are displayed to illustrate the (in)stability of the CO₂ atmosphere (maintained by a CarbonAid diffuser at 10 SLPM) and the intermixing of air into the thorax. First, the effect of rapid hand motions above the thorax are shown. Second, knotting and cutting a suture is simulated inside the thorax. Third, the effect introducing a sucker inside the thorax is visualized. Video available at: [https://www.jtcvs.org/article/S0022-5223\(19\)30936-5/fulltext](https://www.jtcvs.org/article/S0022-5223(19)30936-5/fulltext).

either incision region, regardless of the flow rate. For the cases in which 100% CO₂ could be achieved, the rise time with a tilted diffuser was less than 5 seconds longer

than with a vertically placed diffuser, whereas the application of suction would increase the necessary rise time by approximately 10 seconds, indicating that applying suction mostly impacts the maximum achievable gas concentration.

Disturbances

In addition to the described imaging, we further observed that the CO₂ atmosphere is easily disturbed. It appears that mostly air flows cause drastic mixing of air and CO₂, while gentle motions like knotting or manipulating small instruments have little effect. We illustrated this in [Video 5](#), in which the disturbances are visible as more intense shadow gradients and nonsteady shadow motions. The last section of [Video 5](#) shows the use of a sucker, in which the rapid removal of CO₂ causes turbulent entrainment of air. The 2-dimensional projection may cause the illusion that the sucker is actually blowing air, but it can be observed that introduction of the sucker in the model reduces the overflow of CO₂ from the edge of the thorax model, indicating that part of the delivered CO₂ volume is evacuated via the sucker.

FIGURE 5. Comparison of maximum achieved CO₂ concentrations (*top*) and rise time (*bottom*) at various CO₂ flow rates (1, 4, 7, or 10 SLPM) for all 6 tested devices. The *Tukey box plots* are composed of the 3 replications measured for each device-flow rate combination. *Left*: results at the level of an atrial incision (position 1). *Right*: results at the level of an aorta incision (position 2). CO₂, Carbon dioxide; SLPM, standard liter per minute.

TABLE 2. Summary of maximum CO₂ concentration differences

	CarbonAid				CarbonMini				Temed				Drainage				Tube				Gauze			
CarbonAid	-4	6	7	9	-10	6	14	25	-3	84	91	91	-6	17	48	64	-6	6	15	25				
CarbonMini					-6	0	7	16	1	78	84	82	-2	11	41	55	-2	0	8	16				
Temed									7	78	77	66	4	11	34	39	4	0	1	0				
Drainage													-3	-67	-43	-27	-3	-78	-76	-66				
Tube																	0	-11	-33	-39				
Gauze																								

Pairwise comparison (difference of median) of the max. achieved CO₂ concentrations (%) for 1, 4, 7, or 10 SLPM (left to right subcolumns). Positive values (bold) mean left-side device reaches a higher concentration than the top row device, and italic values mean the opposite. Concentrations were measured in position 2 (~aorta incision) with the device positioned vertically, without application of suction (experiment A). Statistical differences in this pairwise comparison could not be assessed because of limitations of the data set.

DISCUSSION

We set up a simple simulation of the surgical field after sternotomy with CO₂ concentration sensors and an imaging technique to visualize the CO₂ clouds generated by in situ diffusers to understand the effectiveness of CO₂ field flooding and its determining factors.

A first general observation is that the CO₂ atmosphere generated by all diffusers is easily disturbed and does not guarantee prevention of blood-air contact. Visualization showed that CO₂ behaves in one way much like water: It overflows over the edges of the incision and falls straight

down to the floor, while at the same time it is light and fluidic enough to easily generate turbulent flow patterns that enable intermixing and entrainment of air. This observation suggests that CO₂ generally does not reach the head level of the surgical staff, although at high flow rates and depending on the diffuser and its orientation, it is possible that CO₂ is blown up to this level, as was seen with the use of a drainage catheter at 7 and 10 SLPM (Videos 3 and 4). It also takes time to (re)build a CO₂ atmosphere up to its maximum possible concentration at the start of surgery or after disturbing this atmosphere. With approximately 3 minutes of

FIGURE 6. Optical comparison of the gas clouds generated by the 6 different vertically placed diffusers at a flow rate of 7 SLPM. In all panels except for the one labeled “drainage,” a vertical shadow of the caudally placed suction tip is visible, but this was not actively sucking at the time of recording. This figure is a collage of snap shots of the footage that also composes Video 3.

FIGURE 7. Maximum achieved CO₂ concentrations in the thorax model at the level of an aorta incision (position 2), generated with 3 different commercial CO₂ diffusers at various CO₂ flow rates (1, 4, 7, or 10 SLPM). The Tukey box plots are composed of the 3 replications measured for each device-flow rate combination. *Top*: with the diffusers placed vertically, while a caudally placed blood sucker draws out the gas mixture at 5 SLPM. *Bottom*: with the diffusers tilted 45° in the sagittal plane and no active suction. CO₂, Carbon dioxide; SLPM, standard liter per minute.

rise time at 1 SLPM, we anticipate that this atmosphere will constantly be disturbed during surgery and not have the chance to establish its maximum potential, which is already well below the potential of higher flow rates. The exception is the drainage catheter, which reaches its highest possible concentration at 1 SLPM, but with a median rise time greater than 4 minutes it appears to be impractical and still allows approximately 40% of air near the aorta.

From our results, it is obvious that the tested drainage catheter performs the worst of all devices and never creates an atmosphere that can be expected to yield any benefits for the prevention of blood-air contact. The video footage clearly reveals extended turbulences and CO₂-air mixing, while the concentration measurements confirm this with very low values. We hypothesize that at a low flow rate, the gas velocity coming out of the catheter holes does not

entrain much air but needs a long time to fill the thorax, while at higher flow rates, the high velocity jets constantly entrain air and prevent an increase in CO₂ concentration. Although we could not prove that position of the diffuser plays a role in the effectiveness of field-flooding, the location of the surgical incision certainly determines the residual risk of blood-air contact, where incisions deeper in the thorax are deemed safer.

In contrast, the CarbonAid diffuser created a 100% CO₂ atmosphere under most circumstances and does this via a mostly laminar flow that falls down gently from this large diffuser. These observations corroborate the findings of Svenarud with gas samplings.²⁰ Only with the lowest flow rate (1 SLPM) or with the application of suction, does the CarbonAid max out at lower CO₂ concentrations, especially in the region of an aorta incision. The 1 SLPM flow rate in general is unusable for air emboli protection, as explained earlier, because it takes too much time to establish a steady atmosphere and the use of suction would immediately eliminate all the gas. In fact, suction reduces the effectiveness of CO₂ field-flooding in 2 ways: On the one hand, it aspirates part of the delivered CO₂ gas, while on the other hand it causes disturbances and whirls that entrain air in the thorax. However, we need to point out that although it is obvious that a 100% CO₂ atmosphere is the most certain way to prevent air emboli, it is not disproven that a lower value may suffice as well. Future studies will need to identify a safe cutoff to make an objective device selection.

Gerriets and colleagues²¹ concluded that gaseous microemboli contribute to neuropsychologic decline 3 months postoperatively for coronary artery bypass grafting, indicating that clinical studies also need to distinguish between cardiopulmonary bypass components and blood-air contact as the sources of microemboli to fully understand the effectiveness of CO₂ field flooding. Meanwhile, it is a simple, harmless technique that can only yield benefits, especially if some understanding of the gas behavior is present, for which our optical technique is suitable. We have summarized our personal in vitro experience with all tested devices in Table 3.

One covariable we did not assess and that may have an impact on efficiency of CO₂ dispersion is the height and locations at which the diffuser is placed in the thorax cavity. However, the geometry of the diffuser plays a role in how and where it can be placed, and our rectangular thorax model is simple compared with the real anatomy.

Besides this simplification, there are other factors present in an operating theatre not considered in this study. The experiments were performed in a laboratory environment without laminar downflow, fans or heat coming of the various devices normally present in the room. This may have a major impact on the air streams in the theatre and on the CO₂ atmosphere in and above the thorax and warrants further research.

TABLE 3. Summary of practical findings

Devices	CO ₂ flow rate (SLPM)			
	1	4	7	10
CarbonAid	Rise time long. Very sensitive to suction, and disturbances	Highly ineffective with suction or air flow disturbances; acceptable if these are avoided	Ideal combination	Effective, but excessive flow rate
CarbonMini			Acceptable without suction	Acceptable without suction
Temed				
Gauze			Higher flow rate is less effective	
Tube				
Drainage	Insufficient CO ₂ concentration Gas cloud rising high above thorax			
Color Legend	Best option	Acceptable	Not recommended	Worst option

Subjective evaluation of the effectiveness of the different devices used at various flow rates (SLPM) in the rectangular thorax model. The evaluation was based on the authors' interpretation of the rise time and maximum concentration results, the video imaging and unreported tests. CO₂, Carbon dioxide; SLPM, standard liter per minute.

CONCLUSIONS

Our visualization and concentration measurements agreed well and indicate that the CarbonAid device is superior to the other tested diffusors, where improvised devices are clearly inferior to commercial ones.

The flow rate of CO₂ delivery is an important factor, and higher is not always better, but a low flow rate like 1 SLPM has no merits for avoiding blood-air contact in an open thorax. The CO₂ atmosphere generated by any diffusor is unstable, and there are numerous factors that can disturb it, where suction in the surgical field is certainly a key issue.

Conflict of Interest Statement

Authors have nothing to disclose with regard to commercial support.

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