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ORIGINAL RESEARCH

In vitro efficiency of 16 different $Ca(OH)_2$ based CO_2 absorbent brands

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Abstract

Data directly comparing CO_2 absorbents tested in identical and clinically relevant conditions are scarce or non-existent. We therefore tested and compared the efficiency of 16 different brands of $Ca(OH)_2$ based CO_2 absorbents used as loose fill or a cartridge in a refillable canister under identical low flow conditions. CO_2 absorbents efficiency was tested by flowing 160 mL/min CO_2 into the tip of a 2 L balloon that was ventilated with an ADU anesthesia machine (GE, Madison, WI, USA) with a tidal volume of 500 mL and a respiratory rate of 10/min while running an O_2/air FGF of 300 mL/min. After the 1020 mL refillable container was filled with a known volume of CO_2 absorbent (derived from weighing the initial canister content and the product's density), the time for the inspired CO_2 concentration (F_ICO_2) to rise to 0.5% was measured. This test was repeated 4 times for each product. Because the two SpiraLith Ca® products (one with and one without indicator) are delivered as a cartridge, they had to be tested using their proprietary canister. The time (min) for F_ICO_2 to reach 0.5% was normalized to 100 mL of product, and defined as the efficiency, which was compared amongst the different brands using ANOVA. Efficiency ranged from 50 to 100 min per 100 mL of product, and increased with increasing NaOH content (a catalyst), the exception being SpiraLith Ca® cartridge with color indicator (performing as well as the most efficient granular products) and the SpiraLith Ca® cartridge without color indicator (outperforming all others). Results indicated a spherical or bullet shape is less efficient in absorbing CO_2 than broken fragments or cylinders, which in turn is less efficient than a hemispherical (disc) shape, which is in turn less efficient than a solid cartridge with a molded channel geometry. The efficiency of $Ca(OH)_2$ based CO_2 absorbent differs up to 100% on a volume basis. Macroscopic arrangement (cylindrical wrap with preformed channels versus granules), chemical composition (NaOH content), and granular shape all affect efficiency per volume of product. The data can be used to compare costs of the different products.

Keywords CO_2 absorbers · Efficiency · Anesthesia · Equipment · Anesthesia machine · Low flow · Rebreathing

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1 Introduction

There is growing interest in the use of low flow anesthesia because it minimizes anesthetic agent waste and thus its environmental impact and cost. In addition, automation of the low flow delivery process has eliminated any additional burden the technique might impose on the anesthesia provider (more frequent adjustments of vaporizer settings, fresh gas flows, and carrier gas composition) as well as the need for a detailed understanding of the complex effects of rebreathing [1]. Few good reasons remain not to use low flow anesthesia. Still, some have argued that the savings as a result of reduced inhaled agent consumption might be offset or surpassed by the increased use and cost of CO_2 absorbents. In order to be able to address these cost concerns, the absolute and relative efficiency of CO_2 absorbents has to be known. The efficiency of prepacked CO_2 absorbents has recently been described for two different anesthesia machines [2, 3], but "efficiency" was reported in "fractional canister utilization", an efficiency parameter not generalizable to other machine/absorbent combinations because many non-absorbent related factors also affect the efficiency of prepacks: (1) the shape of the plastic container; (2) the type of anesthesia machine used (which includes e.g. the configuration of the breathing system); and (3) the absolute amount of absorbent it contains: the absolute canister content of the same brand differs among different machines, and so does the relative content of the canisters of the different brands for different machines. This study directly compares absorbents under standardized conditions, allowing efficiency to be expressed per volume of actual absorbent.

We tested and compared the efficiency of 16 different brands of CO_2 absorbents used as loose fill in a refillable canister under identical low flow conditions, with "efficiency" being defined as the time for F_ICO_2 to reach 0.5%, normalized to 100 mL of product. Products are compared on a per volume base, not a per weight base for several reasons. First, both prepacks and refillable canisters are filled up to a certain volume, not a certain weight. In addition, the morphology of the granules (and thus the void space between the granules which affects density) affects efficiency, so there will be an inherent difference in efficiency just based on this parameter—neither weight nor volume in and by itself determines efficiency. Finally, we pay per volume of the CO_2 absorbent.

2 Materials and methods

2.1 In vitro setup

Table 1 lists the 16 different commercially available brands that were tested, and includes the manufacturer, major distributor, as well as chemical composition and other properties. The in vitro setup is similar to that used to test prepacks with the Aisys and Zeus [2, 3] (Fig. 1), and the reader is referred to those studies for details. Briefly, a 2 L breathing bag was ventilated in controlled mechanical ventilation mode via a circle breathing system (DAR Adult Breathing Circuit, Covidien, Mansfield, MA) by an ADU® anesthesia machine (GE, Madison, WI, USA) with the following settings: tidal volume 500 mL, respiratory rate 10 / min, I:E ratio1:1, and 0 cm H_2O PEEP. CO_2 from the wall outlet was titrated via a rotameter towards a line pressure distal to the rotameter that corresponds with a 160 mL/min CO_2 flow which was directed into the tip of the breathing bag. Four resistors between the CO_2 rotameter and the tip of the balloon attenuated the backpressure of ventilation on the CO_2 flow. Because the resolution of the rotameter (50 mL/h) is not sufficient for the purposes of this study, the CO_2 flow was titrated towards the pressure in the CO_2 line distal from the rotameter using a previously derived pressure-flow calibration curve. This pressure-flow calibration was constructed by dialing at least five different (arbitrary) rotameter settings, recording the corresponding line pressure, and measuring the corresponding CO_2 flow volumetrically.

Gases were sampled via a sampling port in the D-lite spirometer (GE) by the gas analyzer (M-CAiOV module, GE) which has an average sampling rate of 201 (5) mL/min (average and standard deviation), measured 5 times volumetrically by measuring the time to empty a 250 mL glass syringe (Popper and Sons, Inc. New Hyde Park, NY, USA). The sampled gas plus an average of 39 (0) mL/min of air which the analyzer continuously entrains as the reference gas for its paramagnetic O_2 analysis (also measured volumetrically) were returned from the analyzer's exhaust port to an HME filter (Ref 352/5877, Covidien™, Mansfield, MA) placed between the expiratory limb and the so-called "Compact Bloc® (GE)" onto which a refillable canister was mounted (see Fig. 1). A second HME filter was positioned between the D-lite spirometer and the circle system Y-piece because it was empirically found to minimize artifacts on the capnogram resulting from gas entrainment in the inspiratory limb during the expiratory phase.

CO_2 absorbent granules were poured into a refillable container that was mounted onto the Compact Bloc®, either from a jar or—if the product was unavailable to us as loose fill—from an opened prepacked canister. The plastic refillable container has an internal volume of 1020 mL (measured by water displacement) (Fig. 2). A plastic septum separates the container into two compartments, forcing the gases passing the absorbent to flow from the bottom to the top through the first part of the container, and from the top to the bottom in the second part. To prevent dust from entering the circle breathing system, a 1 cm thick sponge was placed on a plastic grid at the bottom of each compartment. If the canister was filled up such that the granules just covered the septum, the volume available to hold granules ranged from 686 to 730 mL (see Sect. 3).

Before the start of each test, the density of the product to be tested was determined. The granules were poured into a 200 mL plastic cup (measured by water displacement). After slightly overfilling and gently tapping the cup, a plastic ruler was gently swiped over the edges of the cup, removing granules in excess of 200 mL. The empty and filled cup were weighed on a high precision weighing scale (XP1002, Mettler-Toledo, Columbus, Ohio; accuracy 10 mg), and from these data the density of the product was calculated. This process was repeated three times (with new granules each time), and the average value was used as the density of the granules during the upcoming experiment.

Table 1 Product specifications

Product name	$Ca(OH)_2$ %	NaOH %	H_2O %	KOH %	Significant other	Manufacturer	Location**	Distributor	Location**	Reference
LoFloSorb	92.5	0				Intersurgical Ltd.	Wokingham, Berkshire, UK	Intersurgical Ltd.	East Syracuse, NY, USA	a
Amsorb plus*	> 75	0	14.5	0	< $CaCl_2$, $CaSO_4$	Armstrong Medical	Coleraine, UK	Armstrong Medical	Coleraine, UK	b
LithoLyme	> 75	0/LiCl	2–19	0	< 3 LiCl	Allied Healtcare	St Louis, MO, USA	Emergo Europe	The Hague, The Netherlands	b
SoLo	> 97	< 1				Molecular Products	Harlow, Essex, UK	Molecular Products	Harlow, Essex, UK	c
Sodasorb LF	> 80	< 1	15–17	0		GCP Applied Technologies	Epernon Cedex, France			b
Drägersorb free	74–82	0.5–2	14–18	0	3–5 $CaCl_2$	Dräger Medical, Inc.	Lübeck, Germany	Dräger Medical, Inc.	Lübeck, Germany	b
Spherasorb	93.5	1.5	13.5–17.5	0	4% zeolite	Intersurgical Ltd.	Wokingham, Berkshire, UK	Intersurgical Ltd.	Wokingham, Berkshire, UK	a
Atrasorb	68.0–75.0	2.5–3.0				Atrasorb Pharma	Sao Roque,SP, Brazil	N/A	N/A	d
Sofnolime	> 75	< 3	12–19	0		Molecular Products	Harlow, Essex, UK	Molecular Products	Harlow, Essex, UK	b
Sodasorb	70–90	< 4	18.9	0		GCP Applied Technologies	Epernon Cedex, France			b
Intersorb plus	97	3	13.5–17.5	0		Intersurgical Ltd.	Wokingham, Berkshire, UK	Intersurgical Ltd.	Wokingham, Berkshire, UK	a
Medisorb	81	1–2	18	0		Molecular Products	Harlow, Essex, UK	GE	Madison, WI, USA	b,f
FLOW-i*	> 75	< 3	12–19	0		Molecular Products	Harlow, Essex, UK	Getinge	Solna, Sweden	b
Drägersorb® 800 plus*	82	2	16	0		Dräger Medical, Inc.	Lübeck, Germany	Dräger Medical, Inc.	Lübeck, Germany	b
SpiraLith Ca® with indicator	70–85	< 1	14–19	0	< 4 $CaCl_2$	Micropore	Elkton, MD, USA	Micropore	Elkton, MD, USA	e
SpiraLith Ca® NI (no indicator)	70–85	< 1	14–19	0	< 4 $CaCl_2$	Micropore	Elkton, MD, USA	Micropore	Elkton, MD, USA	e

*Obtained from prepacked cylinder

**As indicated on container

[a] http://www.intersurgical.be/content/files/63646/-755104669

[b] Miller

[c] http://www.molecularproducts.com/wp-content/uploads/2017/01/Sofnolime-SoLo-SDS-English-v6.pdf

[d] Product manual

[e] Package insert

[f] Personal communication, Dräger

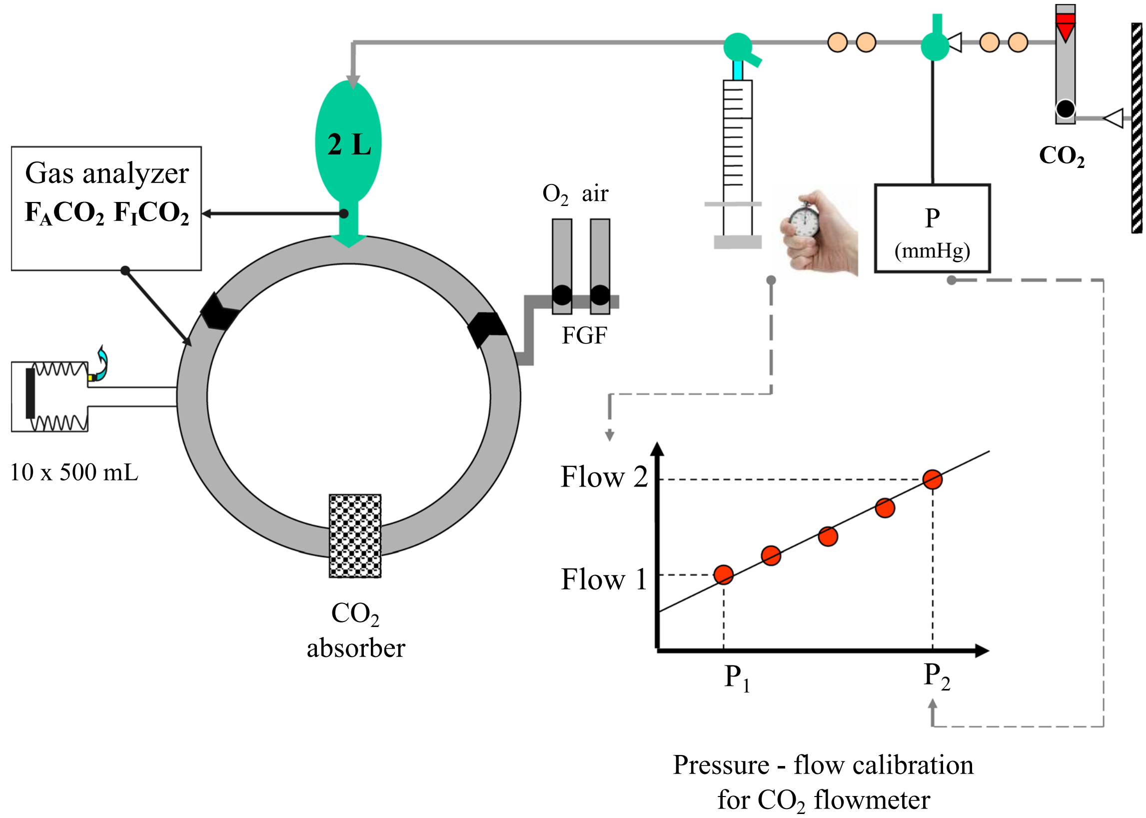

Fig. 1 Experimental setup: CO_2 from the wall outlet is titrated via a rotameter to flow at 160 mL/min into the tip of the breathing bag. Four resistors between the CO_2 rotameter and the tip of the balloon attenuated the backpressure of ventilation on the CO_2 flow. Because the resolution of the rotameter (50 mL/h) is not sufficient for the purposes of this study, the CO_2 flow was titrated towards the pressure in the CO_2 line distal from the rotameter using a previously derived pressure-flow calibration curve. This pressure-flow calibration was constructed by dialing at least five different (arbitrary) rotameter settings, recording the corresponding line pressure, and measuring the corresponding CO_2 flow volumetrically. F_ACO_2 = end-expired CO_2 partial pressure; F_ICO_2 = inspired CO_2 partial pressure

Fig. 2 The ADU refillable canister (left) and the SpiraLith Ca® cartridge and container (right)

After the empty canister was weighed, it was filled with granules until these just covered the top of the septum dividing between the two compartments. The now filled canister was weighed again, allowing the weight of the fresh granules to be calculated (by subtracting the weight of the empty canister) as well as the volume of the fresh granules (using the density). Between runs, the refillable canister was cleaned, water was removed from the breathing hoses, the HME filters were changed, and the system was allowed to run with an empty canister and a high fresh gas flow for at least an hour to remove as much water as possible.

One product had to be treated differently due to its inherently different nature, the SpiraLith Ca® (see Table 1 for details). The absorbent's main ingredient also is $Ca(OH)_2$, but it is made up of a solid sheet that has been wound into a cartridge around a central plastic core, giving it its cylindrical shape with preformed channels (Fig. 2). Two different formulations exist, one with and one without color indicator, and both were tested (4 runs each). A custom-made plastic container is used to house the cylinder (Fig. 2) that is mounted onto the Compact Bloc®. The density of the

SpiraLith Ca® product was calculated by dividing its weight (weight of the entire cartridge minus the weight of the plastic core plus any inner and outer wraps) by its volume (the volume of the cartridge minus the volume of the plastic core, both calculated as height*π*radius^2; also see Fig. 2).

Immediately after the freshly filled canister (with granules or the SpiraLith Ca®) was placed onto the Compact Bloc®, ventilation was started as described above with O_2 and air fresh gas flows of 0.15 L/min each—this defined the start of the study. Spirometry data, inspired and expired O_2 and CO_2 partial pressures, and the pressure in the CO_2 inflow line (used to calculate CO_2 inflow—see reference [2] for details) were downloaded every minute using RUGLoop (DEMED, Temse, Belgium). Each test ran until the F_ICO_2 had increased above 0.5%, a threshold commonly used to replace the absorbent. For each brand, four test runs were done (all of the same lot), except for SoLo, for which the four runs were repeated with an interval between tests of 2 months to document consistency of the experimental setup. Therefore, for one product, SoLo, a total of eight runs was done.

2.2 Data analysis

Absorbent use on a volume basis was calculated by dividing the time (min) for F_ICO_2 to reach 0.5% by the volume of the fresh absorbent in the canister prior to the start of each experiment, which then was normalized to 100 mL of product.

The following parameters of the different products were compared: CO_2 inflow, F_ACO_2–F_ICO_2, time (min) until F_ICO_2 reached 0.5% per 100 mL of product, and time (min) until F_ICO_2 reached 0.5% per 100 g of product. F_ACO_2–F_ICO_2 is a measure of both ventilation and CO_2 inflow according to the general air equation:

$F_ACO_2 = F_ICO_2 + VCO_2$/alveolar ventilation

Groups were compared using ANOVA followed by a Holm-Sidak test to analyze between group differences (all data were normally distributed) (Sigmaplot, Systat Software Inc., San Jose, CA, USA). Statistical significance was defined by $p < 0.05$. Data are presented as mean (standard deviation).

3 Results

Results are presented in Tables 1 and 2. ANOVA indicated that differences amongst groups were significant ($p < 0.05$). Those groups that did not differ according to the Holm-Sidak test used to analyze between group differences carry the same symbol in the last two columns of Table 2. Efficiency ranged from 50 to 100 min per 100 mL of product, and increased with increasing NaOH content (a catalyst), the exception being the SpiraLith Ca® cartridge with color indicator (performing as well as the most efficient granular products) and the SpiraLith Ca® cartridge without color indicator (outperforming all others). A spherical or bullet shape is less efficient in absorbing CO_2 than broken fragments or cylinders. Broken fragments or cylinders are less efficient than a hemispherical (disc) shape. A hemispherical (disc) shape is less efficient than a solid cartridge with a molded channel geometry.

4 Discussion

We tested and compared the efficiency of 16 different brands of CO_2 absorbents used as loose fill in a refillable canister under identical low flow conditions. Table 2 and Fig. 2 organizes the different brands from top to bottom according to their efficiency per 100 mL. Efficiency is the time per 100 mL of absorbent for the F_ICO_2 to rise to 0.5% when 160 mL/min CO_2 flows into the tip of a 2 L balloon that is being ventilated with an ADU anesthesia machine with a tidal volume of 500 mL and a respiratory rate of 10/min while running a O_2/air FGF of 300 mL/min, with approximately 700 mL of granules contained in a 1020 mL refillable container (the SpiraLith Ca® cartridge is placed in a specially designed container). Three factors determined absorbent life per 100 mL of a product: macroscopic arrangement (cylindrical wrap with preformed channels versus granules), chemical composition (NaOH content), and granular shape.

Efficiency improves as the NaOH content increases, the exception being the SpiraLith Ca® cartridge with indicator (performing as well as the most efficient granular products) and SpiraLith Ca® cartridge without indicator (outperforming all others). The SpiraLith Ca® results are compared to the loose fill results because both are refillable absorbents—but and instead of letting the granules randomly settle, the CO_2 absorbent is pre-molded into a consistent shape.

The uniform, consistent geometry of the solid sheets wound into a cartridge around the plastic core forms channels with a consistent arrangement. This arrangement seems to maximize the contact surface for CO_2 (allowing greater utilization of the chemicals contained in the cartridge on a volume basis) and eliminates random channeling (that occurs in granules), which explains the low variability in efficiency observed in this study (see coefficient of variation in Table 2) and in previously published work [2, 3].

The efficiency measurement, which is the fundamental basis for comparing the absorbents, is based upon the determination of the volume of absorbent. For the granular absorbents, the method for determining volume is based upon dividing the measured weight by the volume of the cup (200 mL) and should result in a comparable measurement

Table 2 Study results

Brand	Macro shape	NaOH	Micro shape	Weight fresh product in compact bloc	Density	Volume fresh product in compact bloc	CO_2 flow	$F_ACO_2–F_ICO_2$	Time per 100 mL of product for F_ICO_2 to reach 0.5%			
		(%)		(g)	(g/100 mL)	(mL)	(mL/min)	(%)	min	CV (%)		
LoFloSorb	Granular	0	Spheres	461 (5)	67 (0)	687 (7)	160 (3)	4.4 (0.1)	50 (2)	5	¶	
Amsorb plus	Granular	0	Broken cylinders	449 (11)	65 (1)	688 (16)	160 (2)	4.3 (0.1)	56 (3)	6	¶	†
LithoLyme	Granular	0/LiCl	Broken cylinders	464 (17)	67 (0)	691 (26)	161 (1)	4.3 (0.1)	59 (3)	5	§	†
SoLo	Granular	< 1	Broken fragments	452 (16)	64 (1)	707 (30)	160 (1)	4.3 (0.1)	61 (5)	8	§	†
SodaSorb LF	Granular	< 1	Broken cylinders	529 (4)	73 (1)	730 (15)	161 (1)	4.1 (0.1)	66 (2)	4	§	++
Drägersorb Free	Granular	0.5–2	Hemisphere	544 (9)	77 (0)	709 (12)	160 (1)	4.3 (0.2)	69 (2)	4		++
Spherasorb	Granular	1.5	Spheres	517 (14)	75 (0)	686 (18)	161 (2)	4.3 (0.2)	70 (1)	1		++
AtraSorb	Granular	2.5–3.0	Bullet	584 (14)	80 (0)	726 (18)	160 (3)	4.3 (0.1)	72 (1)	2	¶¶	++
Sofnolime	Granular	< 3	Broken fragments	561 (9)	78 (0)	721 (12)	161 (1)	4.2 (0.3)	77 (2)	3	¶¶	
Sodasorb	Granular	< 4	Broken cylinders	586 (14)	85 (1)	690 (21)	161 (2)	4.3 (0.1)	78 (4)	5	¶¶	
Intersorb Plus	Granular	3	Broken cylinders	564 (29)	80 (1)	701 (32)	158 (0)	4.2 (0.1)	88 (6)	6	‡	
Medisorb	Granular	1–2	Broken fragments	544 (6)	77 (1)	711 (10)	161 (1)	4.2 (0.1)	88 (4)	5	‡	
FLOW-i	Granular	< 3	Broken fragments	559 (9)	79 (2)	704 (26)	160 (2)	4.2 (0.1)	90 (2)	2	‡	
Drägersorb 800+	Granular	2	Hemisphere	578 (4)	82 (0)	702 (5)	160 (2)	4.3 (0.1)	91 (1)	1	‡	
SpiraLith Ca® with indicator*	Cartridge	< 1	preformed channels	824 (11)**	88 (1)	933 (0)***	160 (1)	4.5 (0.1)	95 (1)	1	‡	$
SpiraLith Ca® NI (no indicator)*	Cartridge	< 1	preformed channels	815 (7)**	87 (1)	933 (0)***	161 (1)	4.3 (0.2)	100 (1)	1		$

The CO_2 flow and $F_ACO_2–F_ICO_2$ difference did not differ between products ($p = 0.774$ and 0.052, respectively). Time (min) per 100 mL of product for F_ICO_2 to reach 0.5% did differ among the different products; groups with identical symbols (¶ † § ¶¶ ‡ $) do not differ

CV coefficient of variation

*Tested in custom-made refillable plastic container different from that used to test granular products—see text for details; **Does not include weight of plastic core nor wrap around cartridge

***Does not include volume of plastic core (67 mL) for all absorbents. Since SpiraLith Ca® absorbent is non-granular, the volume measurement is different from the granular absorbents, and therefore a direct comparison with the granular absorbents is not possible. Our goal is to provide the reader with some idea on how their efficiencies compare. Thus, in order to compare the SpiraLith Ca® efficiency results to those of the granular products, the method for measuring SpiraLith Ca® volume needs to be justified as equivalent to the method of volume measurement used for the granular products. The volume measurement for the SpiraLith Ca® is directly based upon the absorbent cartridge geometry and is not derived from the density value—measuring the density in a manner analogous to the granular products would require the SpiraLith Ca® cartridge to be fragmented to fit in a 200 mL cup. But this will alter the performance of the product, thereby making the results irrelevant. For these reasons, we believe the imperfect comparison we made is clinically relevant and fair. If desired, the results can always be expressed and compared on a weight basis by using the density data in Table 1, that for the SpiraLith Ca® excludes the central core and wrapping material.

Within the group of granular products, efficiency improves with increasing content of the catalyst NaOH. While the removal of $Ba(OH)_2$ and KOH has eliminated the clinical risk of sevoflurane decomposition into compound A, trace amounts of compound A may still be produced in the presence of NaOH. This has been the impetus for several companies to develop low NaOH or NaOH free products. While these trace amounts of compound A are clinically irrelevant, some users may still prefer not to use the NaOH containing products for medicolegal purposes. Obtaining the exact composition of several products has been found challenging by us and other authors [4].

Finally, for products with the same or similar NaOH content, a spherical or bullet shape is less efficient in absorbing CO_2 than broken fragments or cylinders, which in turn is less efficient than a hemispherical (disc) shaped configuration, and a solid absorbent cartridge is most efficient. Difference in shape likely affects how well CO_2 can penetrate into the center of the absorbent, thus affecting efficiency.

"Efficiency" of a CO_2 absorbent can be defined in different ways. When considering prepacks, it is expressed as the FCU, the fraction of the canister used per hour until F_ICO_2 reaches 0.5% after inflow of a specific amount of CO_2 [2, 3]. When considering loose fill (this study), it is expressed as the time 100 mL of product lasts until F_ICO_2 reaches 0.5%. Efficiency can also be defined as the time 100 g of product lasts until F_ICO_2 reaches 0.5%, but this would be largely irrelevant for cost calculations for either prepacks or loose fill (even if they would be sold on a weight basis), because refillable canisters are filled up to a certain volume, not a certain weight. Finally, efficiency can also be defined as the ratio of the amount of CO_2 absorbed over the maximum CO_2 absorption capacity. Each definition conveys different information.

The limitations of in vitro studies have been previously discussed: (1) CO_2 loads in real life vary; (2) no canister is used for more than 24 h straight; and (3) the degree of rebreathing might be slightly different from that in the experimental setup because O_2 was not removed from the system [2]. Preliminary clinical data indicate that the effect of these factors on canister life is small. Finally, because many factors are known to affect CO_2 absorbent efficiency, care should be taken to extrapolate the results of this study beyond the conditions described in this study.

To summarize, we tested and compared the efficiency of 16 different brands of CO_2 absorbents used as loose fill in a refillable canister under identical low flow and CO_2 loading conditions. Three factors determined absorbent life per 100 mL of product: macroscopic arrangement (cylindrical wrap with preformed channels vs. granules), chemical composition (NaOH content), and granular shape. The data can be used to compare costs of the different products.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human participants and/or animals This work did not to include research involving human participants and/or animals.

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