When to replace a CO_2 absorber?

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Abbreviations:

FGF:	**Fresh gas flow**
MV:	**Minute ventilation**
VCO_2:	**CO_2 production**
$F_{ET}CO_2$:	**End-expired CO_2 concentration**
F_ICO_2:	**Inspired CO_2 concentration**
FCU:	**Fractional Canister Use**
	expressed in %: 100/[time (h) to F_ICO_2 = 0.5%]
	expressed in fraction: 1/[time (h) to F_ICO_2 = 0.5%]
fR:	**Fraction of rebreathing**

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Introduction

This narrative review will provide the reader with a rational approach towards CO_2 absorbent replacement. First, we explain the rebreathing concept and the need for CO_2 absorbers. This sets the stage for studying what happens to the F_ICO_2 if a canister would be exhausted. The effects of a rising F_ICO_2 on the patient is reviewed. After briefly reviewing the absorption process, a method is offered to quantify CO_2 absorbent use: Fractional Canister Use (FCU). FCU allows different brands to be compared in terms of cost and environmental impact. Next, we discuss the relationship between $F_{ET}CO_2$, F_ICO_2, and MV. This provides the reader with crucial insight in how to use the F_ICO_2 to determine when the CO_2 absorbent has to be changed. The review ends by reviewing other methods to guide CO_2 absorbent replacement (such as color changes), only to conclude that the only rational approach is to monitor the F_ICO_2 and change the CO_2 absorbent once the F_ICO_2 has reached 0.5% (3-4 mmHg), but not sooner. If the water vapor pressure is ignored, 1% of 1 atm or 760 mmHg ≈ 7.6 mmHg, and 0.5% ≈ 3-4 mmHg.

The reader will note that the number of references for a narrative review is low: the number of manuscripts dealing with quantitative aspects of CO_2 absorbers is very limited. Several aspects can be derived from first principles or from well-established physiologic principles and thus are unreferenced unless published before by the authors.

Why we need CO_2 absorbers?

An anesthesia workstation is composed of a ventilator and a delivery system for inhaled anesthetics. A circle breathing system allows exhaled gases to be re-inhaled. This is particularly useful to reduce waste of inhaled anesthetics: because the patient

Prior presentation: The work has not been presented before.

does not take up all the anesthetic gas from the inhaled gas mixture, the exhaled gas still contains significant amounts of anesthetic gas that can literally be recycled. However, the exhaled gases also contain CO_2, and excessive concentrations have dose dependent toxic effects (Table IA)[1,2]. A CO_2 absorber therefore is an essential component of the circle breathing system. Low F_iCO_2 can be accepted: the maximum allowable F_iCO_2 in space for example is 0.5% (4 mmHg) for 100 days, and 1.3% (10 mmHg) for 24 hours (Table IB)[1,2].

How much would F_iCO_2 rise without CO_2 absorber?

The amount of CO_2 that is absorbed by a fresh canister depends on the amount of CO_2 the patient exhales and the degree of rebreathing in the workstation. The amount of exhaled CO_2 is the sum of endogenously produced CO_2 and exogenously administered and absorbed CO_2 (e.g. from a CO_2 pneumoperitoneum). While accurately measuring the amount of exhaled CO_2 is challenging, endogenous VCO_2 in adults during anesthesia has been reported to range from 0.130 - 0.140 L/min but varies substantially[3,4]. The amount of CO_2 resorbed from a CO_2 pneumoperitoneum averages 0.030 L/min[5-7].

While the sum of exhaled endogenous and exogenous CO_2 determines the maximum amount of CO_2 that could reach the absorber, the fraction of this amount that actually does reach the absorber depends on de degree of rebreathing. The degree of rebreathing itself depends on the fresh gas flow (FGF) coming out of the common gas outlet and the patient's MV. The MV determines the total amount of gas that has to be provided to the ventilator bellows. This gas can be composed exclusively of fresh gas coming from the common gas outlet (FGF) or it can be composed of a mixture of rebreathed and fresh gas. When the FGF equals or exceeds MV (= no rebreathing), no or minimal amounts of CO_2 will reach the canister. Once FGF is reduced below MV (= rebreathing), exhaled gas will have to ensure that the ventilator can deliver the required MV. For example, if the FGF is only 75% of the MV, the other 25 percent of the MV will have to consist of exhaled gas. And if the FGF is half the MV, 50 percent of the MV will have to consist of exhaled gas. If the FGF is only 25% of the MV, the other 75 percent of the MV will have to consist of exhaled gas. And finally, if FGF is reduced to equal oxygen uptake by the patient, virtually all of the MV will have to consist of exhaled gas. These examples (0, 25, 50, 75 and 100% rebreathing) are plotted in Figure 1 for a MV of 5 L/min (the figure ignores the effect of O_2 uptake by the patient). It can be seen that there is a negative correlation between the rebreathing fraction (fR) and FGF, and fR becomes (theoretically) zero once FGF becomes identical to MV. The fraction of the total amount of exhaled CO_2 that reaches the absorbent varies accordingly.

Table IA. — Health effects of increased inspired CO_2 concentrations[1,2]. Physiological tolerance time for various CO_2 concentrations and acute health effect of high concentrations of CO_2

PHYSIOLOGICAL TOLERANCE			ACUTE HEALTH EFFECTS	
ppCO2		Maximum Exposure Limit (min)	Duration of Exposure	Effects
mm Hg	%			
3.8	0.5%	Indefinite		
7.5	1.0%	Indefinite		
11	1.5%	480		
15	2.0%	60	Several hours	Headache, dyspnea upon mild exertion
23	3.0%	20	1 hour	Headache, sweating, dyspnea at rest
30	4.0%	10	(4-5%)	
38	5.0%	7	Within few minutes	Headache, dizziness, increased blood pressure, uncomfortable dyspnea
45	6.0%	5	1-2 minutes ≤16 minutes Several hours	Hearing, visual disturbances Headache, dyspnea Tremors
53	7.0%	<3	(7-10%)	
68	9%	N/A	Few minutes 1.5 minutes to 2 hours 9% for 5 minutes	Unconsciousness, near unconsciousness Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing Lowest published lethal concentration
75	10%	N/A	(>10-15%)	
113	15%	N/A	1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness
128	17%	N/A	(17-30%) Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death

Table IB. — Health effects of increased inspired CO_2 concentrations[1,2]. Spacecraft Maximum Allowable Concentration (SMAC) for CO_2.

Exposure Time	SMAC (%)	Equivalent SMAC (mm Hg)
1 hour	2.0%	15
24 hours	1.3%	10
7 to 180 days	0.7%	5
1000 days	0.5%	4

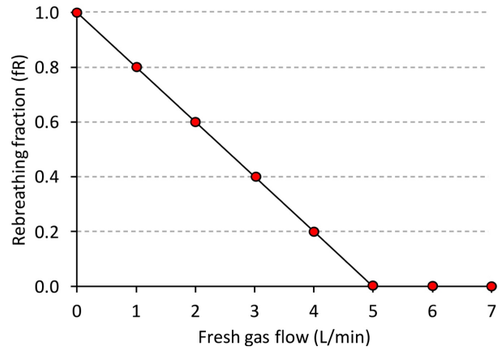


Fig. 1 — Effect of fresh gas flow on rebreathing. While MV ventilation is held constant at 5 L/min, there is a negative linear correlation between fresh gas flow (FGF) and rebreathing of exhaled gas. Rebreathing becomes zero once FGF equals minute ventilation (assuming an ideal work station). Rebreathing becomes 100% once the FGF equals the sum of uptake by the patient, leaks, and possible losses from gas sampling (= closed circuit anesthesia). See text for details. The figure ignores the effect of O_2 uptake by the patient.

Now that we understand the amounts of CO_2 entering the workstation and how the degree of rebreathing depends on FGF and MV, let us consider how high the CO_2 concentration would rise in the circuit in the absence of a CO_2 absorber (or in the presence of a completely exhausted CO_2 absorber). Using an in vitro setup with a VCO_2 of 0.160 L/min and a MV of 5 L/min we measured what happened to the F_iCO_2 with different FGF (0.5, 2, 3, and 6 L/min) (Figure 2). With a FGF of 0.5 L/min, 90% of the exhaled gases are rebreathed, causing F_iCO_2 to rise to 17% (≈129 mmHg, a lethal concentration. With a FGF of 2 L/min or 40% rebreathing, F_iCO_2 rises to 4.4% or ≈33 mmHg, and with a FGF of 3 L/min FGF or 60% rebreathing, F_iCO_2 rises to 1.3% or ≈10 mmHg. Finally, with a FGF of 6 L/min, there is no rebreathing and F_iCO_2 = 0. Contrary to rebreathing where there is a negative correlation between FGF and fR (Figure 1), the increase in F_iCO_2 is inversely proportional with FGF (Figure 2)[8].

Composition (Table II)

When limestone ($CaCO_3$) is burnt at 1000 °C in a kiln, CO_2 is removed, yielding CaO (quick lime or burnt lime). Mixing CaO with water yields $Ca(OH)_2$, the key ingredient of contemporary CO_2 absorbents (Figure 3)[9]. When CO_2 is absorbed, the cycle is then reversed: CO_2 reacts with $Ca(OH)_2$, yielding $CaCO_3$, water and heat. The water and heat serve to humidify and warm the cold, bone-dry gases coming out of the hospital gas outlets.

While sevoflurane degradation into compound A has never, ever been a clinical issue, removing KOH as a catalyst has made the issue completely moot. The use of catalyst NaOH only generates minute amounts of compound A, but if this would provide medicolegal grounds for concern, the clinician can select a product completely devoid of KOH and NaOH (see Table II)[10]. Products completely devoid of NaOH are less efficient on a per weight

Table II. — Properties of prepacked CO2 absorbents for Aisys and Zeus[11,12].

Brand name	Distributor	Primary absorbent	NaOH content vol%	Weight of fresh granules g		Canister life min untill FICO2 = 0.5%		$FCU_{0.5}$ %/h		Time untill 0.5% F_iCO_2/100 g min	
				Zeus	Aisys	Zeus	Aisys	Zeus	Aisys	Zeus	Aisys
Amsorb Plus	Armstrong M		0	821 (34)	777 (31)	865 (88)	624 (59)	7.0 (0.7)	9.7 (0.9)	105 (7)	81 (9)
LoFloSorb	Intersurgical		0	1002 (10)	924 (10)	940 (97)	765 (59)	6.4 (0.7)	7.9 (0.6)	94 (9)	83 (7)
Medisorb EF	Molecular Products		< 2.5	-	721 (4) - 712 (13)	-	593 (30)	-	10.15 (0.5)	-	83 - 89
Drägersorb Free	Dräger		< 2.5	959 (16)	-	1077 (69)	-	5.6 (0.4)	-	112 (8)	-
SpheraSorb	Intersurgical	$Ca(OH)_2$	2.5	1117 (16)	1055 (6)	1043 (145)	934 (49)	5.9 (0.9)	6.4 (0.3)	93 (12)	89 (4)
Drägersorb 800+	Dräger		2.5	941 (25)	-	1056 (56)	-	5.7 (0.3)	-	112 (5)	-
CO2ntrol	Molecular Products		2.5	1145 (7)	-	1435 (66)	-	4.2 (0.2)	-	125 (6)	-
Medisorb	Molecular Products		2.5	-	816 (18)	-	901 (109)	-	6.8 (1.0)	-	111 (13)
LithoLyme	Allied HC		(*)	1114 (53)	1002 (20)	1289 (171)	960 (114)	4.7 (0.6)	6.3 (0.75)	115 (11)	96 (10)

F_iCO_2 = inspired CO_2 concentration (%); $FCU_{0.5}$ = fractional canister usage with F_iCO_2 threshold = 0.5% - see text for details
(*) Catalyst is LiCl

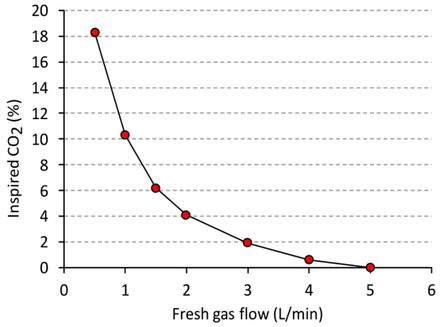


Fig. 2 — Effect of lowering fresh gas flows (FGF) on the inspired CO_2 concentration in the absence of a CO_2 absorber. When an anesthesia workstation ventilates a 2 L breathing bag with a 5 L/min minute ventilation with a 0.160 L/min CO_2 inflow, $FICO_2$ varies inversely proportional with FGF. See text for details.

basis. Why the compound A issue continues to be cited occasionally is enigmatic: all contemporary commercially available products are safe[10].

Quantifying canister life

The absorbent in commercially available products is organized in granules. They are supplied either as prepacked single-use anesthesia workstation specific plastic canisters ("prepacks") or in bulk for use with refillable canisters. This review will only consider prepacks (Table II). Canister life for various products has been tested under standardized conditions (5 L/min MV and 0.160 L/min CO_2 inflow) over a range of FGF. Because lower FGF increase rebreathing and thus the CO_2 load to the absorber, when the absorber is exhausted, F_iCO_2 will rise sooner, faster and higher when lower FGF are used (Figure 4)[11,12].

Prepacks from different brands differ in their performance[11,12]. When Aisys specific prepacks are tested under identical conditions, Amsorb Plus and LoFloSorb are found to start to exhaust sooner than Medisorb and SpheraSorb (Figure 5). Total

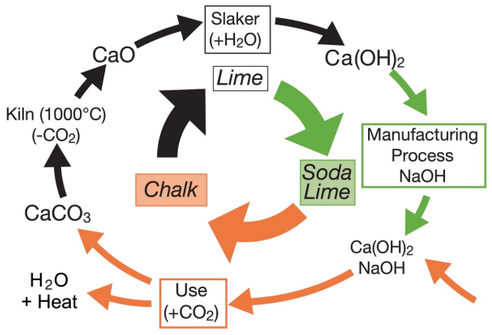


Fig. 3 — The $Ca(OH)_2$ - $CaCO_3$ cycle.

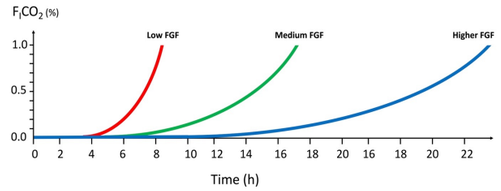


Fig. 4 — Typical exhaustion pattern. Because lower FGF increase rebreathing and thus the CO_2 load to the absorber, the inspired CO_2 ($FICO_2$) will rise sooner, faster and higher as lower FGF are used. This graph is for illustrative purposes only (not based on data).

absorbent content, granular shape and size, and the presence of NaOH all affect canister life (Table II). Prepacks for different workstations differ in shape, size, and total absorbent content. Performance results of a particular brand for one anesthesia workstation therefore do not apply to that of another workstation. Similarly, the relative performance of prepacks of different brands with one particular workstation does not translate into the same relative performance with another workstation.

To compare different brands, the concept of fractional canister use (FCU) has been introduced[11]. The derivation of the FCU concept is beyond the scope of this review. The FCU describes the fraction of a particular canister that is used per hour in vitro under a specified set of circumstances (5 L/min MV and 0.160 L/min CO_2) when a specific FGF is used with a particular workstation. It is calculated as (100/number of hours until F_iCO_2 reaches 0.5%), and is expressed as %/hour (or, alternatively, as fraction per hour). Multiplying the FCU of a canister with the cost of 1 canister or the global warming potential of 1 canister yields the cost or environmental impact of a prepack at a certain FGF for the above standard settings. Values for different prepacks for 2 different

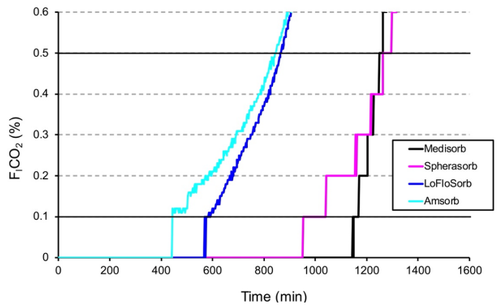


Fig. 5 — Exhaustion patterns[11]. Exhaustion patterns of 4 different prepacked absorbers for the Aisys workstation tested with 0.160 L/min VCO_2, 5 L/min minute ventilation, and 1.2 L/min. Amsorb Plus and LoFloSorb start to exhaust sooner than Medisorb and SpheraSorb. Allowing the inspired CO_2 (F_iCO_2) to rise to 0.5% (upper thick black line) instead of 0.1% (upper thick black line) increases canister life substantially. See text for details.

workstations can be found in Table II; these values assume the canister is replaced once the F_iCO_2 reaches 0.5% (≈ 3-4 mmHg)[11,12].

Figure 5 alerts the reader to the importance of selecting the F_iCO_2 at which a canister is going to be replaced (= the F_iCO_2 replacement threshold). Amsorb Plus and LoFloSorb can be noticed to start to exhaust sooner than Medisorb and SpheraSorb (the former two do not contain NaOH as a catalyst)8,11. If the clinician would replace the canister immediately upon noticing an F_iCO_2 of 0.1%, canister life of Amsorb Plus and LoFloSorb would only be approximately 50% of that of Spherasorb and Medisorb. But if the F_iCO_2 would be allowed to rise to 0.5% or 3-4 mmHg, the following happens: (1) canister life of the Amsorb Plus doubles; (2) canister life of Amsorb Plus and LoFloSorb as well as that of Medisorb and SpheraSorb become identical; and finally (3) canister life of both Amsorb Plus and LoFloSorb become approximately 2/3 that of Medisorb and SpheraSorb (instead of 50%). Because the F_iCO_2 curve starts to rise faster once F_iCO_2 moves past 0.5% or 3-4 mmHg (especially with FGF below 1 L/min), any extra gains in terms of extending canister life will be small if a higher F_iCO_2 threshold is chosen. Still, could F_iCO_2 be allowed to rise further clinically? To be able to answer this question, we need to understand the relationship between F_iCO_2, $F_{ET}CO_2$, and MV.

Adding it up Relationship between $F_{ET}CO_2$, F_iCO_2, and MV[13]

The relationship between VCO_2, F_iCO_2, and $F_{ET}CO_2$ is described by the alveolar air equation. Most anesthesiologists are familiar with the abbreviated version of this formula: $F_{ET}CO_2 = VCO_2$/alveolar ventilation. This equation is quoted in any basic pulmonary physiology course, and clinically means that an increase in VCO_2 will increase $F_{ET}CO_2$ if alveolar ventilation is unchanged, and that increasing alveolar ventilation will decrease $F_{ET}CO_2$ if VCO_2 is unchanged. F_iCO_2 is not always considered because it does not apply to clinical situations relevant for pulmonologists. However, it does apply to breathing in closed spaces where CO_2 is being (re)inhaled, e.g. space stations, submarines, fire protective gear, diving gear, or an anesthesia circle breathing system. Because it is highly relevant to the use of CO_2 absorbers, it is worthwhile considering mass balances at the Y-piece of a circle breathing system.

For didactical purposes, let us assume the following: (1) gases are mixed homogeneously and instantaneously in each compartment we consider (lung volume and in- and expired tidal volume); (2) in- and expired volumes do not differ; (3) dead space ventilation is absent, therefore the $F_{ET}CO_2$ represents the CO_2 concentration in the lungs. The amount of CO_2 leaving the Y-piece per minute is the sum of the amount entering the Y-piece plus the amount of CO_2 being added by the patient, VCO_2. The total amount of CO_2 entering the Y-piece per minute is the product of MV and F_iCO_2, and similarly the total amount of CO_2 leaving the Y-piece per minute is the product of MV and $F_{ET}CO_2$:

CO_2 amount leaving Y-piece = CO_2 amount entering Y-piece + CO_2 production

$MV^*F_{ET}CO_2 = MV^*F_iCO_2 + VCO_2$

This equation can be rewritten in a 3 different ways that each convey a slightly different aspect that is relevant for a proper understanding of CO_2 absorbent management:

$F_{ET}CO_2 = F_iCO_2 + VCO_2/MV$

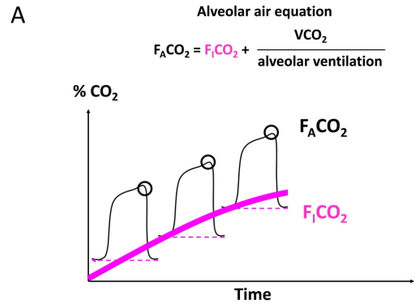
$VCO_2 = MV\ (F_{ET}CO_2 - F_iCO_2)$

$F_{ET}CO_2 - F_iCO_2 = VCO_2/MV$

The first equation implies that a rise in F_iCO_2 will cause $F_{ET}CO_2$ to rise by the same amount if VCO_2 and MV are left unchanged: the effect of F_iCO_2 on $F_{ET}CO_2$ is additive (Figure 6). The second equation explains what would happen if ventilation would be increased to curb the effect of F_iCO_2 on $F_{ET}CO_2$ while keeping VCO_2 constant: the difference between $F_{ET}CO_2$ - F_iCO_2 would decrease because the same amount of CO_2 would be distributed over a larger number of breaths (if respiratory rate would be increased) or over larger breaths (if tidal volume would be increased). The third equation explains what happens if MV is increased when F_iCO_2 starts to rise because the absorbent is starting to exhaust. This is explained in the next paragraph.

When a circle breathing system is used, the alveolar air equation alone no longer suffices to describe the relationship between $F_{ET}CO_2$, F_iCO_2, and MV because the F_iCO_2 becomes dependent on MV due to rebreathing: it is often overlooked that rebreathing increases not only when FGF is decreased but also when MV is increased. Increasing ventilation will cause the gases in the circle breathing system to more often pass the CO_2 absorber and thus increase CO_2 absorption and decrease canister life, but in the case of an exhausting absorber will also cause F_iCO_2 to increase because the contact time between the CO_2 and the exhausting granules decreases (Figure 6). If ventilation is increased to curb the effect of the rising F_iCO_2 on $F_{ET}CO_2$, F_iCO_2 will rise (due to increased rebreathing) and the difference between F_iCO_2 - $F_{ET}CO_2$ will decrease (as per $F_{ET}CO_2$ - $F_iCO_2 = VCO_2/MV$). This is illustrated in Figure 6.

A



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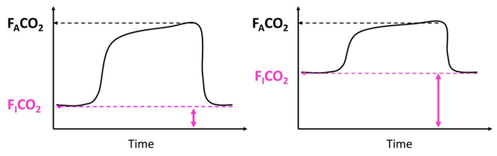

Fig. 6 — The capnogram and management of the exhausting absorbent: permissive hypercapnia or isocapnic hyperventilation. A. Permissive hypercapnia: The effect of F_ICO_2 on $F_{ET}CO_2$ is additive: if VCO2 and minute ventilation are constant, a rise in F_ICO2 will cause the $F_{ET}CO_2$ to rise to the same degree. B. Isocapnic hyperventilation: Hyperventilating the patient during canister exhaustion will decrease the $F_{ET}CO_2$ - F_ICO_2 difference (because the same amount of CO_2 is distributed over more breaths or larger tidal volumes) and increases the F_ICO_2 (because rebreathing in the circle system increases).

Managing the exhausting absorber

Once the F_ICO_2 starts to rise to 0.1% (≈0.7 mmHg), no immediate action has to be taken: the F_ICO_2 should be allowed to rise to 0.5% (3-4 mmHg). Because the effect of the F_ICO_2 on the $F_{ET}CO_2$ is additive according to the alveolar air equation, the $F_{ET}CO_2$ will rise by a similar degree, 0.5% (3-4 mmHg). Such an increase in $F_{ET}CO_2$ is well tolerated by all but the frailest patients we take care of (e.g. patients with intracranial hypertension or pulmonary hypertension). While additional gains in canister life become smaller as F_ICO_2 rises above 0.5% (3-4 mmHg), the F_ICO_2 could nevertheless be allowed to rise further. Two approaches can be taken. One is permissive hypercapnia: the F_ICO_2 is allowed to rise until the $F_{ET}CO_2$ has risen to a level the clinician no longer deems acceptable[13]. The other one is to maintain isocapnia by progressively increasing ventilation. The F_ICO_2 will rise even more but $F_{ET}CO_2$ will remain normal, and will remain a good reflection of the arterial CO_2 partial pressure under these conditions[13]. In this second scenario, the limiting factor that will ultimately make the clinician decide to insert a new canister is the degree of hyperventilation deemed acceptable. Summarized, while a F_ICO_2 replacement threshold of 0.5% (3-4 mmHg) keeps the middle ground between optimizing canister efficiency and minimizing patient impact (i.e. elevated $F_{ET}CO_2$ or elevated airway pressures), the F_ICO_2 can be allowed to rise further: the decision to replace a CO_2 absorber ultimately is a clinical decision based on the degree of hypercapnia or hyperventilation deemed acceptable by the clinician. Still, in routine clinical practice we recommend to replace canisters once F_ICO_2 reaches 0.5% (or 3-4 mmHg), but not sooner.

Other means to guide cannister replacement

Many $Ca(OH)_2$ based CO_2 absorbents contain color indicators that change color once the granules become exhausted. The color change proceeds along the path the CO_2 takes within the canister, depending on where the exhaled gases enter the canister. Color indicators are less than an optimal guide to steer canister replacement. One of these color indicators is e.g. ethyl violet, a pH-activated color indicator[14]. CO_2 absorption causes the pH of the absorbent to decrease which causes the indicator to change color, which gives a crude indication of the remaining CO_2 absorption capacity. Different products may use different indicators which may have different colors[15]. The color change reverts to the original color when left overnight, thus the color per se is a poor indicator of the remaining absorption capacity. Color change may also indicate desiccation of alkali-free absorbents (e.g Amsorb Plus)[15].

Some departments may also elect to "routinely" change canisters, e.g. on a specific day of the week. This wasteful practice may be driven by e.g. a fear of having to "open" a circle breathing circuit in the middle of a case. However, most modern workstations will keep the circuit closed when removing the canister. Many also offer a "pause" mode, during which FGF, agent delivery and ventilation are briefly interrupted and the canister can be exchanged without wasting gases into the operating room. This procedure can also be used to remove water from the hoses in the expiratory limb caused by cooling the exhaled warm and humid gases. Exchanging a canister takes less than a minute. A brief decrease in end-expired anesthetic agent concentration can be noticed due to adsorption of anesthetic onto the granules and because the gas in between the granules initially contains no anesthetic agent. This may require a transient increase in agent delivery, which will be taken care of automatically by workstations functioning in target controlled mode. Some of these automated target control workstations also have a backup system that automatically increases FGF once F_ICO_2 exceeds a certain threshold, e.g. 1% (≈ 7 mmHg).

Conclusion

For many clinicians, the CO_2 absorber remains a somewhat enigmatic part of the anesthesia workstation. Contemporary absorbents use $Ca(OH)_2$ which interacts with CO_2 to form $CaCO_3$, H_2O and heat. Canister exchange should only be guided by the F_ICO_2. Replacing a canister when the F_ICO_2 reaches 0.5% (3-4 mmHg) provides a good trade-off between minimizing waste (and thus cost and pollution) and optimizing patient care.

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