

Using Amsorb to Detect Dehydration of CO₂ Absorbents Containing Strong Base

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Background: Because Amsorb changes color when it dries, the authors investigated whether Amsorb combined with different strong base-containing carbon dioxide absorbents signals dehydration of such absorbents.

Methods: Five different carbon dioxide absorbents (1,330 g) each topped with 70 g of Amsorb were dried in an anesthesia machine (Modulus CD, Datex-Ohmeda, Madison, WI) with oxygen (Amsorb layer at the fresh gas inflow site). As soon as a color change was detected in the Amsorb, the authors tested the samples for a change in weight and carbon monoxide formation from 7.5% desflurane or 4% isoflurane. In a different experiment with the five absorbents, Amsorb was layered at the drying gas outflow site. In further experiments, the authors tested for a color change in Amsorb from drying and rehydrating and from drying with nitrogen. Finally, they dried a mixture of Amsorb and 1% NaOH and examined it for color change.

Results: In the experiments with Amsorb layered at the inflow, the Amsorb changed color when the water content of the samples was only marginally reduced (to a mean 13.6%), and no carbon monoxide formed. With Amsorb layered at the outflow, it changed color when the mean water content of the samples was reduced to 8.8%, and carbon monoxide formation was detected to varying degrees. The color change was independent of the drying gas and could be reversed by rehydrating. Adding NaOH to Amsorb prevented a color change.

Conclusions: Dehydration in strong base-containing absorbents can reliably be indicated before carbon monoxide is formed when Amsorb is layered at the fresh gas inflow. The authors assume that the indicator dye in Amsorb changes color on drying because of the absence of strong base in this absorbent.

It cannot be determined in clinical routine when carbon dioxide absorbents are drying out from exposure to the fresh gas flow in an anesthesia machine. Desiccation in strong base-containing absorbents is connected with carbon monoxide (CO) formation by degradation of the volatile anesthetics desflurane, enflurane, and isoflurane.¹⁻³ In clinical practice, this can lead to pathologically increased concentrations of carboxyhemoglobin in the patient.⁴⁻⁶

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Amsorb (Armstrong, Coleraine, Northern Ireland) is a recently developed absorbent that contains no strong bases and that produces no CO, even when completely dry.⁷ Whenever we dried this absorbent, we observed a color change from white to violet, which we never noted previously when drying any strong-base absorbent. In the present investigation, we aimed to determine whether decreasing moisture content in strong-base absorbents can be reliably indicated by a color change in Amsorb when it is combined with different such absorbents, before CO forms from anesthetic degradation. We tested this first with Amsorb layered at the fresh gas inflow site of the absorbent canister in an anesthesia machine. We then tested it with Amsorb layered at the outflow site of a canister.

We further tested whether the Amsorb changed color because of dehydration or as the result of a reaction with oxygen. In addition, we rehydrated dry Amsorb to determine whether the color change resulting from dehydration is reversible. We hypothesized that the indicator dye in Amsorb would not change color in the presence of strong bases. To test this, we added 1% sodium hydroxide (NaOH) to pulverized Amsorb and observed the color of this mixture during drying.

Methods

Testing Color Change and CO Formation in Absorbents Dried in an Anesthesia Machine with Amsorb Layered at the Fresh Gas Inflow: Series A

The upper and lower carbon dioxide absorbent canisters (Dameca, Copenhagen, Denmark) of an anesthesia machine (ModulusCD, Mini-Absorber-System, Datex-Ohmeda, Madison, WI) were filled with fresh samples of five absorbents containing strong base. The different absorbents were: Intersorb, Spherasorb (both Intersurgical, Wokingham, Berkshire, UK), Baralyme (Allied Health Care Products Inc., St. Louis, MO), Drägerorsorb800, and Drägerorsorb800Plus (both Dräger, Lübeck, Germany). The lower canister was filled with 700 g of the strong base absorbent and the upper canister with 630 g that was then covered with 70 g of fresh Amsorb (Armstrong, Coleraine, Northern Ireland). The anesthesia machine was set to manual or spontaneous breathing with the adjustable pressure-limiting (APL) valve completely open and the Y-piece closed. The fresh gas supply of the anesthesia machine was set to deliver 10 l/min of pure oxygen to the circle system (fig. 1). The samples were observed every hour for a change in color of the Amsorb layer by the same two persons, a photo was taken, and

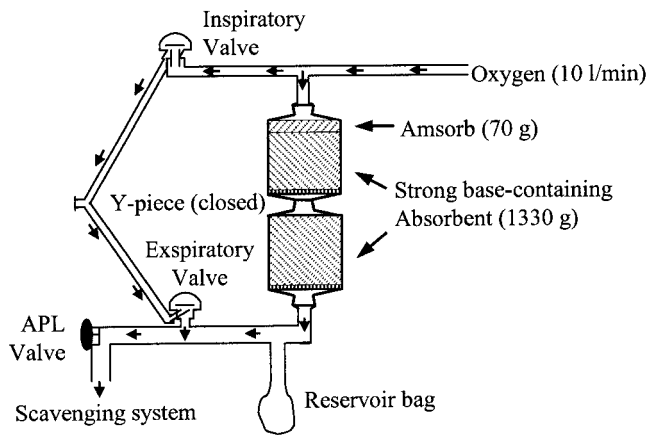


Fig. 1. Experimental set-up in series A: Different strong-base absorbents (1,330 g) were filled into a double canister of an anesthesia machine (Modulus CD, Ohmeda) with Amsorb (70 g) layered at the top of the upper canister, *i.e.*, at the fresh gas inflow. The anesthesia machine was set to manual/spontaneous breathing with the Y-piece closed and the adjustable pressure-limiting (APL) valve completely open. The fresh gas supply was adjusted to deliver 10 l/min of pure oxygen. A change in color of the Amsorb layer indicated a decrease in water content of the entire absorbent.

each of the canisters was weighed (PJ3000, Mettler-Toledo, Greifensee, Switzerland) to determine the decrease in the water content. We regarded the color change as complete when the color of the entire Amsorb layer was identical to that of a separate sample of pure Amsorb that had been dried to a constant weight by a stream of oxygen.

As soon as the entire Amsorb layer had changed color, we passed 7.5% desflurane (Suprane[®], Baxter, Deerfield, IL) or 4% isoflurane (Forane[®], Abbott, Queensborough, UK) in oxygen (5 l/min) through the canisters and monitored the resulting CO concentrations using a polarographic CO sensor (range, 0–1,000 ppm; CO-3E 300, Sensoric, Bonn, Germany). The sensor was placed in sidestream arrangement with the sampling line connected to the gas outflow tubing 20 cm above the absorbent's surface. Before use, the CO sensor was calibrated with a certified tank (900 ± 20 ppm CO in N₂; AGA, Schwechat, Austria). Inlet and outlet anesthetic concentrations were measured with anesthetic agent-specific infrared analyzers (the isoflurane with IRINA, Dräger, Lübeck, Germany; the desflurane with M1026A, Hewlett-Packard, Andover, MA). Outflow concentrations of CO and the anesthetic agents were recorded every 20 s. We continued the inflow of desflurane for at least 15 min after the concentration of the anesthetic, measured at the outlet, had reached the set value of 7.5%. If there was no CO detectable within that time, the desflurane inflow was discontinued, and when the anesthetic was no longer measurable at the outlet, we stopped measuring the CO concentration. The experiments with isoflurane were discontinued when the outlet isoflurane concentration reached the set concentration of 4%. All

the experiments were carried out three times with each absorbent and anesthetic agent.

Testing Color Change and CO Formation with Amsorb Placed at the Gas Outflow: Series B

To determine whether it mattered where the Amsorb was placed, in these experiments a glass cylinder (90 mm diameter, 200 mm length) was filled in turn with 540 g of each of the five absorbents containing strong base and covered with 60 g Amsorb. Oxygen was passed through the samples at a flow of 5 l/min, adjusted with the use of a mass flow controller (Mass-Flo[®] 1259, MKS Instruments, Andover, MA). The humidity of the gas was less than 100 ppm (Gas Analyzer 1301, Brüel & Kjær, Nærum, Denmark). The samples were assessed hourly for color change and weight decrease by the same two persons who completed the evaluations in series A. As soon as a color change was noted in the Amsorb layer (T_{color}), 0.5% isoflurane was added to the oxygen flow for 60 min, and outflow concentrations of isoflurane and CO were recorded every 20 s as described for series A. From the CO concentration curves, we determined CO maximum values (CO_{Max}) and calculated total CO formation (CO_{Total}), considering the gas flow and the duration of exposure, as follows:

$$\text{CO}_{\text{Total}}[\text{ml}] = \text{gas flow} [\text{mL} \cdot \text{sec}^{-1}] \cdot k \cdot \sum_{i=1}^k \text{conc}_i[\%] \cdot \Delta t [\text{sec}]$$

conc_i : mean concentration during time interval Δt
k : number of time intervals Δt during exposure

These experiments were repeated with absorbent samples we dried completely after detecting a color change in Amsorb. The samples were considered to be completely dry when the loss of weight within a 6-h period was less than 0.3 g (equivalent to a loss of 0.05% in sample weight). CO formation was then determined as described previously. We regarded the weight lost through complete drying to be equivalent to the water content of the fresh samples. We considered the difference between the water content of the fresh samples and the weight decrease in the corresponding samples dried to the point of color change to be the water content of the latter.

Testing Whether the Color Change in Amsorb Is the Result of Dehydration: Series C

To determine the reduction in water content in Amsorb when it first changed color, two 10-g samples of pure Amsorb were dried with a flow of oxygen (5 l/min) directed through the samples for 75 min. Every 15 min the samples were checked for a change in color and a decrease in weight. The water content of the fresh samples was considered equivalent to the samples' weight decrease at the end of the drying period. The water content at color change was calculated as in series B.

To verify that the color change in Amsorb is the result of dehydration, we first mixed two samples of 90 g

Table 1. Weight Loss in Absorbents when Drying was Indicated by Amsorb Layered at the Fresh Gas Inflow

	Intersorb	Spherasorb	Baralyme	Draegersorb800	Draegersorb800Plus
Weight loss [%] of the absorbent in the upper canister (including Amsorb)	1.3 ± 0.0	1.3 ± 0.0	1.2 ± 0.0	1.2 ± 0.1	1.4 ± 0.1
Weight loss [%] of the absorbent in the lower canister	0.2 ± 0.0	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.0	0.3 ± 0.1

Experimental series A: weight loss, representing decline in water content, in five different strong-base absorbents filled into the CO₂-absorbing canisters in an anesthesia machine (n = 3). Weight loss was determined when the Amsorb layered at the top of the upper canister (at the gas inflow) changed color. There was a relatively small weight loss in both canisters, as it took no more than 1 h of drying for the entire Amsorb layer to change color. Values are mean ± SD.

Drägersorb800Plus with 10 g Amsorb and dried them with oxygen (5 l/min) for 20 h. The samples were then monitored for a change in color and a decrease in weight. Thereafter, we rehydrated the samples, adding distilled water equal in weight to the weight lost on drying. The samples were shaken and inspected 8 h later for color.

To rule out a specific effect of oxygen on the color change in Amsorb, four samples of 90 g Drägersorb-800Plus covered with 10 g Amsorb were dried for 20 h in the same manner as described previously, but two of the samples were dried with nitrogen instead of oxygen. During the first 5 h, the samples were checked hourly for a change in color and a decrease in weight. The water content of the fresh samples was considered equivalent to the samples' weight decrease at the end of the drying period; the water content at color change was calculated as in series B.

Color Change in Amsorb in the Presence of Sodium Hydroxide: Series D

Amsorb granules mixed with NaOH (weight relationship, 99:1) and Amsorb granules alone were separately ground into a fine powder using a blender. Oxygen (flow, 0.1 l/min) was directed through samples (20 mm in height) containing 10 g of the ground Amsorb or 10 g of the mixture. After 1 h and 20 h the samples were assessed with respect to color and weight. Finally, the samples were oven-dried at 120°C for 60 min and then weighed again. The experiments were performed in parallel four times. The sum of the weight loss after 20 h of flow drying and the weight loss after oven drying was regarded as the original water content of the samples. The water content of the partly dried samples after 1 h and 20 h was calculated as described in series B.

Statistical Analysis

Results are presented as the mean ± SD. In series B, the variables of CO production in the partly dried samples were compared with those of the completely dried samples using the Mann-Whitney U test. The same test was used to compare the water content of the samples with and without NaOH in series D. For statistical calculations, the standard software version of SPSS 7.5.2G (SPSS Inc., Chicago, IL) was used. A one-tailed probabil-

ity of less than 0.05 was regarded as statistically significant.

Results

Color Change and CO Formation in Absorbents Dried in an Anesthesia Machine with Amsorb Layered at the Fresh Gas Inflow

In series A, with Amsorb placed at the fresh gas inflow of the ModulusCD canisters, the color change in Amsorb was complete in 1 h of drying. Only Amsorb and none of the other absorbents changed color. The weight loss in the upper absorbent canister was 1.3 ± 0.1% of the fresh absorbent's weight. In the lower canister, the weight loss was 0.2 ± 0.04% (individual values in table 1). The set concentrations of the volatile anesthetic agents were reached at the outflow within 5 min, and no CO was detected at the outflow when isoflurane was directed through the samples. Also in the experiments with desflurane continued for 15 min after the set concentration was reached, no CO was detected at the outflow during the entire experiment.

Color Change and CO Formation with Amsorb Placed at the Gas Outflow

In series B, in which Amsorb was layered at the outflow, the Amsorb layer changed color in a mean of 7.5 ± 4 h (T_{Color}). The calculated water content of the samples at T_{Color} was 8.8 ± 2.0% compared with an initial mean water content of 14.1 ± 1.6%. When isoflurane (0.5%) was added to the O₂ flow at T_{Color}, we determined maximum CO concentration values of 75 ± 74 ppm. When the experiment was repeated with completely dried samples, the maximum CO concentration was 526 ± 228 ppm (see fig. 2 for time course). CO formation as calculated was significantly lower in the experiments with only partly dried *versus* in those with completely dried absorbent (4.7 ± 2.8 ml *vs.* 82.7 ± 61.8 ml; individual values in table 2).

Effect of Dehydration on the Color Change in Amsorb

In the first experiment of series C, in which pure Amsorb samples were dried to determine the water content at the point of color change, a thin layer at the

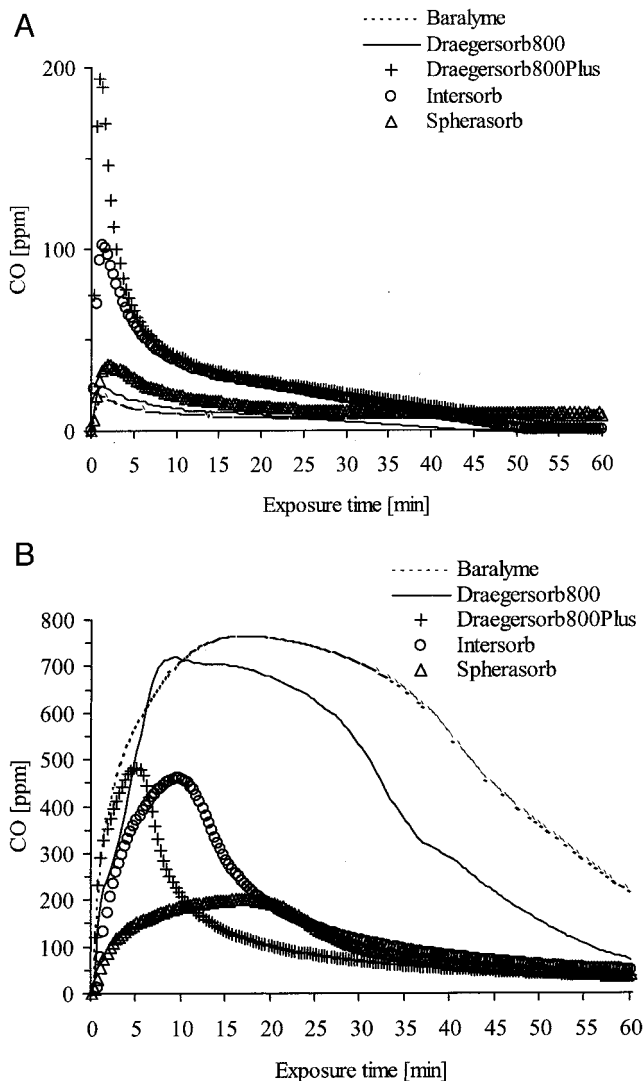


Fig. 2. (A) Time course of CO concentrations arising from five strong-base absorbents after color change in Amsorb layer at the outflow of drying gas is shown (experimental series B). (B) CO concentration curves in the respective experiments with completely dried samples. In these experiments, CO formation was induced for 60 min by adding 0.5% isoflurane to oxygen directed through the samples at a flow of 5 l/min. When the absorbent samples are only partly dried to the point of color change in Amsorb, the CO concentration levels are far lower (e.g., A vs. B). Note the different scales of the y-axes.

inflow site had changed color at the first assessment (after 15 min). The water content at this point was 8.1–8.6% (*vs.* 14.5–14.9% in the fresh Amsorb samples). In 45 min, all the granules had changed color at a water content of 0.6–1%.

In the second experiment of series C, in which two Drägersorb800Plus samples mixed with Amsorb were dried for 20 h, the Amsorb granules had turned violet, contrasting clearly with the white Drägersorb800Plus granules. The weight loss of the two samples was 15.6% and 15.7%. After water equal in weight to the weight lost was added, the color of the Amsorb granules reversed

from violet to white within 8 h, the Drägersorb800Plus not having changed color during the entire experiment.

In the third experiment, in which Drägersorb800Plus covered with Amsorb was dried with oxygen or nitrogen, the Amsorb layer always changed color after 3 h of drying, irrespective of the gas used. Nor did the water content at the point of color change vary with the drying gas (5.6–5.8% in the samples dried with oxygen, and 5.2–5.8% in the samples dried with nitrogen).

Color Change in Amsorb in the Presence of Sodium Hydroxide

In series D, pulverized samples of pure Amsorb and of Amsorb plus NaOH were compared for water content and color change resulting from drying. We determined initial water content of $13.9 \pm 0.2\%$ for Amsorb and $13.5 \pm 0.4\%$ for Amsorb plus NaOH, with no statistically significant difference between the groups. The pure Amsorb samples started to change color at the inflow site after 1 h at a water content of $12.5 \pm 0.1\%$. At the same time point, in the samples consisting of Amsorb plus NaOH, the water content was $12.2 \pm 0.2\%$, and no color change was detected. As drying continued, the height of the colored layer advanced in the samples with pure Amsorb, and after 20 h, at a water content of $1.2 \pm 0.2\%$, these samples were violet throughout. At a comparable water content of $1.1 \pm 0.2\%$ after the same drying period, no more than 2 mm of Amsorb plus NaOH turned violet at the inflow site.

Discussion

Color Change and CO Formation in Absorbents Dried with Amsorb

The present investigation has shown that, when Amsorb is added to a canister containing a strong-base absorbent, the Amsorb undergoes a color change that indicates that it and the paired absorbent are drying out. Layering Amsorb over the strong-base absorbent at the inflow of the gas into the canister allows a decrease in the absorbent's moisture content to be reliably indicated before CO is formed from anesthetic degradation. In contrast, when Amsorb is layered at the outflow, dehydration is not signaled until the strong base-containing absorbent has reached a level of dehydration at which CO begins to form.

In the anesthesia system we used (ModulusCD, Mini-Absorber-System, Ohmeda), Amsorb was placed on top of the absorbent material in the upper canister because in this machine the fresh gas flow is from the top and the flow of expired breath is from the bottom (fig. 1). This means that the absorbent begins to dry from the top of the canister, whereas carbon dioxide is first absorbed at the bottom. Thus, layering Amsorb at the top makes it possible to note a color change early in this circle sys-

Table 2. Water Content and Carbon Monoxide (CO) Formation in Absorbents when Drying was Indicated by Amsorb Layered at the Fresh Gas Outflow

	Intersorb	Spherasorb	Baralyme	Draegersorb800	Draegersorb800Plus
Initial water content [%]	14.2	11.8	13.4	15.3	15.8
Drying period to color change T_{color} [h]	9, 12	6, 4	4, 4	4, 6	12, 12
Water content [%] at T_{color}	7.8, 6.1	7.4, 8.6	10.4, 10.5	12.2, 10.8	7.1, 7.3
CO_{max} [ppm] after T_{color}	102	36	19	25	194
CO_{total} [ml] after T_{color}	6.6	4.1	2.5	1.8	8.4
Complete drying period T_{D} [h]	96	72	136	72	72
CO_{max} [ppm] after T_{D}	460	201	767	719	483
CO_{total} [ml] after T_{D}	49.6	32.2	170.3	125.4	36.1

Experimental series B: two samples (540 g) each of five different strong-base absorbents were covered with a layer of Amsorb (60 g) and dried with oxygen directed through them from the bottom at a flow of 5 l/min until a color change in Amsorb was detectable (T_{color}). Half of each pair of samples was then dried completely (T_{D}). Isoflurane (0.5%) was added to the oxygen flow for 60 min both in the samples dried to T_{color} and those dried to T_{D} , and the maximum CO concentration (CO_{max}) at the outflow and the amount of CO formed (CO_{total}) were determined for both drying times.

tem. Dehydration was already detectable when the water loss was only $1.3 \pm 0.1\%$ of the total weight of the absorbent material. The water content of these samples at this point can be estimated as $13.6 \pm 1.5\%$ if the initial water content of the fresh samples is assumed to be the same as determined in series B ($14.1 \pm 1.6\%$). At such minimal dehydration, CO does not yet form.^{1,2} We verified this in the present investigation when 7.5% desflurane or 4% isoflurane were directed through the samples immediately after dehydration was detected and we measured no CO.

To detect dehydration in the Ohmeda-GMS canister system and in the Narcomed-Dräger system, Amsorb should be filled into the bottom of the canister because in these circle systems the fresh gas enters at the bottom and the expired breath at the top. With respect to the amount of Amsorb needed in relationship to a strong base-containing absorbent, our results show that the Amsorb layer does not need to represent more than 10% of the total weight. In any case, it is important that the Amsorb layer be visible to the anesthesiologist⁸ and that it covers or is covered by, depending on the system, the strong base-containing absorbent completely.

In some anesthesia systems—as in the Dräger-Sulla-808-ISO-System—the fresh gas and the expired breath pass through the absorbent canister in the same direction. If Amsorb were layered at the inflow in these machines, the color change resulting from drying would be mistaken for the color change attendant on incipient exhaustion of carbon dioxide-absorbing capacity. When we tested Amsorb at the outflow, we did not see a color change in Amsorb until the water content of the absorbent samples was reduced to $8.8 \pm 2.0\%$. This was connected with CO formation in all the absorbents; still, the maximum CO concentration values were much lower than those arising from the completely dried samples (75 ± 74 ppm vs. 526 ± 228 ppm; table 2). We assume that in clinical anesthesia a greater amount of absorbent, or a higher isoflurane or desflurane concentration, would elicit higher and possibly toxic CO concentration levels because CO formation in absorbents

depends on the absorbent quantity and the anesthetic identity and concentration.^{1,9} We therefore conclude that combining strong base-containing absorbents with Amsorb layered at the canister outflow cannot be generally regarded as a safe test for drying.

Effect of Dehydration on the Color Change in Amsorb

When we dried pure Amsorb, a color change was first elicited in some granules at the inflow site at a water content of less than 9%. All the granules changed color at a water content of less than 1%. We assume that in all the experimental series the water content of Amsorb at color change was similar (approximately 8% at most). As in experimental series A, the water content of the total absorbent material at color change of Amsorb was estimated as $13.6 \pm 1.5\%$; Amsorb must have been dried to a greater degree than the total absorbent material. This can be explained by the fact that Amsorb was layered at the fresh gas inflow where the absorbent in an anesthesia machine dries first.¹⁰

Further evidence that the color change in Amsorb results specifically from a loss of moisture was provided by the fact that drying the mixture of Amsorb and Draegersorb800Plus caused a color change only in the Amsorb, and that rehydration caused a reversal of this change in color. It has been suggested that dried absorbents can be refreshed by the addition of water.¹¹ Such refreshment could conceivably be confirmed by a color change in Amsorb granules from violet to white if dry Amsorb is mixed with the dried absorbents.

The experiment in which drying absorbents with nitrogen instead of oxygen provoked an identical color change in Amsorb and confirmed that the color change in Amsorb is the result of drying and not a possible reaction with oxygen.

Possible Mechanism of Color Change

In Amsorb and in all the tested absorbents containing strong base, the indicator dye ethyl violet is added to signal the exhaustion of carbon dioxide-absorbing capac-

ity.¹² The color change in ethyl violet, an acid–base indicator, is the result of hydroxyl (OH[−]) elimination. When pH decreases below the critical pH value of 10.3, or if the system is dehydrated, ethyl violet appears in its colored form. One could assume that the addition of the strongly hygroscopic NaOH and KOH to Ca(OH)₂ prevents complete dehydration and the resulting color change. However, the experiments with pulverized Amsorb and pulverized Amsorb containing NaOH yielded nearly the same water loss for both groups of samples. Thus, the mechanism of color change in the samples without NaOH remains to be explained.

Clinical Implications

Adding an Amsorb layer to strong base-containing absorbents at the fresh gas inflow of carbon dioxide-absorbent canisters appears to allow the reliable early detection of moisture decrease in the absorbent by exploiting Amsorb's property of changing color when drying. With this method, absorbent dehydration is detected before CO formation in the absorbent occurs. This could provide a greater margin of patient safety when strong base-containing absorbents are used.

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