failure will be spotted before a sudden need for tank O₂ arises and none is available.

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Intravenous dead space and patient safety in patient-controlled analgesia

To the Editor:

A patient-controlled analgesia (PCA) machine consists of a pump which accepts demands for analgesia from a push-button operated by the patient. When a demand is granted, the pump delivers a preprogrammed dose of analgesic into a sideport in the patient's intravenous (iv) line. A carrier iv infusion then carries any injected drug into the patient. As a safety feature, the pump is usually programmed so that for a period (usually 5–15 min) after the delivery of a dose, further requests are ignored ("lockout period"). This interval is selected so that at the end of the lockout period the patient should be able to sense whether or not the last dose was adequate, and thus demand more analgesia if there is still excessive pain at the end of the lockout period.

The time needed for a PCA machine to discharge drug into the connecting tubing depends on the dose size and pump model, but is typically well under one minute. However, while it takes under one minute to inject the drug, it may take a much longer time for the patient to receive all of the dose because of the time required to flush all drug from the PCA dead space once the drug has completely left the PCA pump ("flush time"). Large flush times are either due to large dead space or small carrier flows. Low carrier flows may be encountered whenever the carrier iv line is clamped too tightly, the infusion rate is set too low, or when the iv bag becomes empty. Large dead space volumes may exist with the addition of extension tubing between the patient's iv catheter and the PCA sidearm connection. Flush time for the situation of a single PCA dose can be determined from the general relation "time = volume/flow" as *flush time* = V_{ds}/F , where V_{ds} is the PCA deadspace and F is the carrier flow through the iv line (see Figure).

The analysis presented here points to a new source of concern with PCA use. Patient lockout times usually range from 5 to 15 min. As the flush time approaches the lockout interval, patients will be unable to determine if a particular dose of analgesic is adequate before the

FIGURE Flush time (vertical axis; minutes) for various carrier flows (horizontal axis; $\text{ml} \cdot \text{hr}^{-1}$) and dead volumes (1, 2, 3 and 4 ml (from bottom to top)). Note the dramatic increase in flush time with low carrier flows (e.g., iv KVO). See also examples above.

end of the lockout interval. When baseline iv flows are low, such as when patient's iv is in "KVO" mode, and/or when the PCA deadspace is large, the flush time to deliver all of the analgesic to the patient can be far in excess of typical patient lockout settings. This concept is illustrated further in the examples below. When this situation occurs, patients may repeatedly request additional analgesic at the end of each lockout interval, ultimately resulting in a situation where the patient gets excessive medication when the drug in the dead space finally gets to the patient. This may explain the need for occasional "naloxone rescues" in patients on PCA.

Example 1 (Normal operation)

Carrier flow (F) of $50 \text{ ml} \cdot \text{hr}^{-1}$

Dead space (V_{ds}) of 1 ml

Flush time = $1 \text{ ml} \cdot 50 \text{ ml}^{-1} \cdot \text{hr}^{-1} = 1.2 \text{ min.}$

Example 2 (KVO operation with large dead space)

Carrier flow (F) of $5 \text{ ml} \cdot \text{hr}^{-1}$

Dead space (V_{ds}) of 5 ml

Flush time = $5 \text{ ml} \cdot 5 \text{ ml}^{-1} \cdot \text{hr}^{-1} = 60 \text{ min.}$

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