Volumetric Capnography

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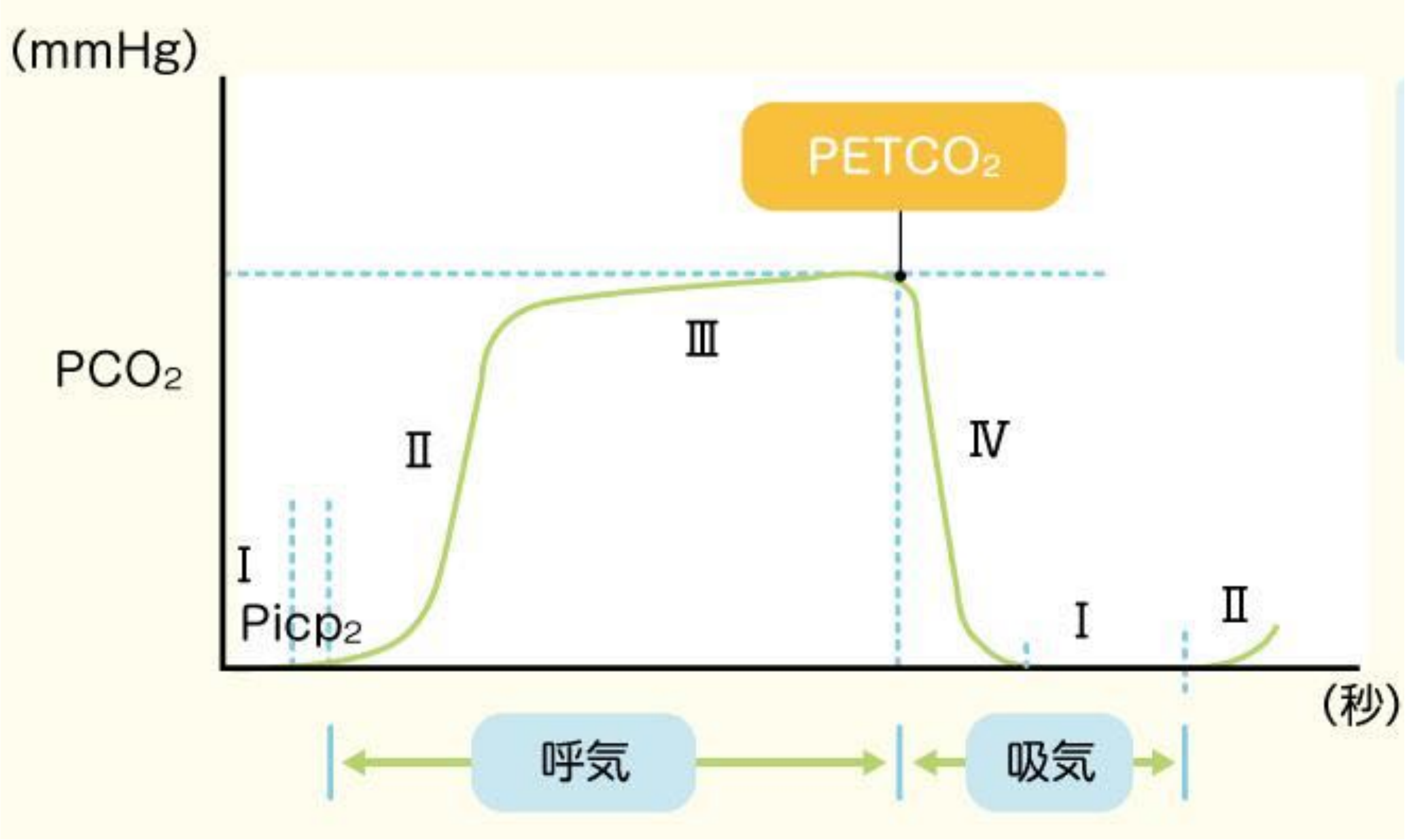
ゴール

- Volumetric capnographyとは何かを定義できる。
- Volumetric capnographyの波形の成り立ちを説明できる。
- CO_2産生から呼出までの過程を説明できる。
- Volumetric capnographyで得られるデータの解釈ができる。
- ベッドサイドで”使う”ことができる。

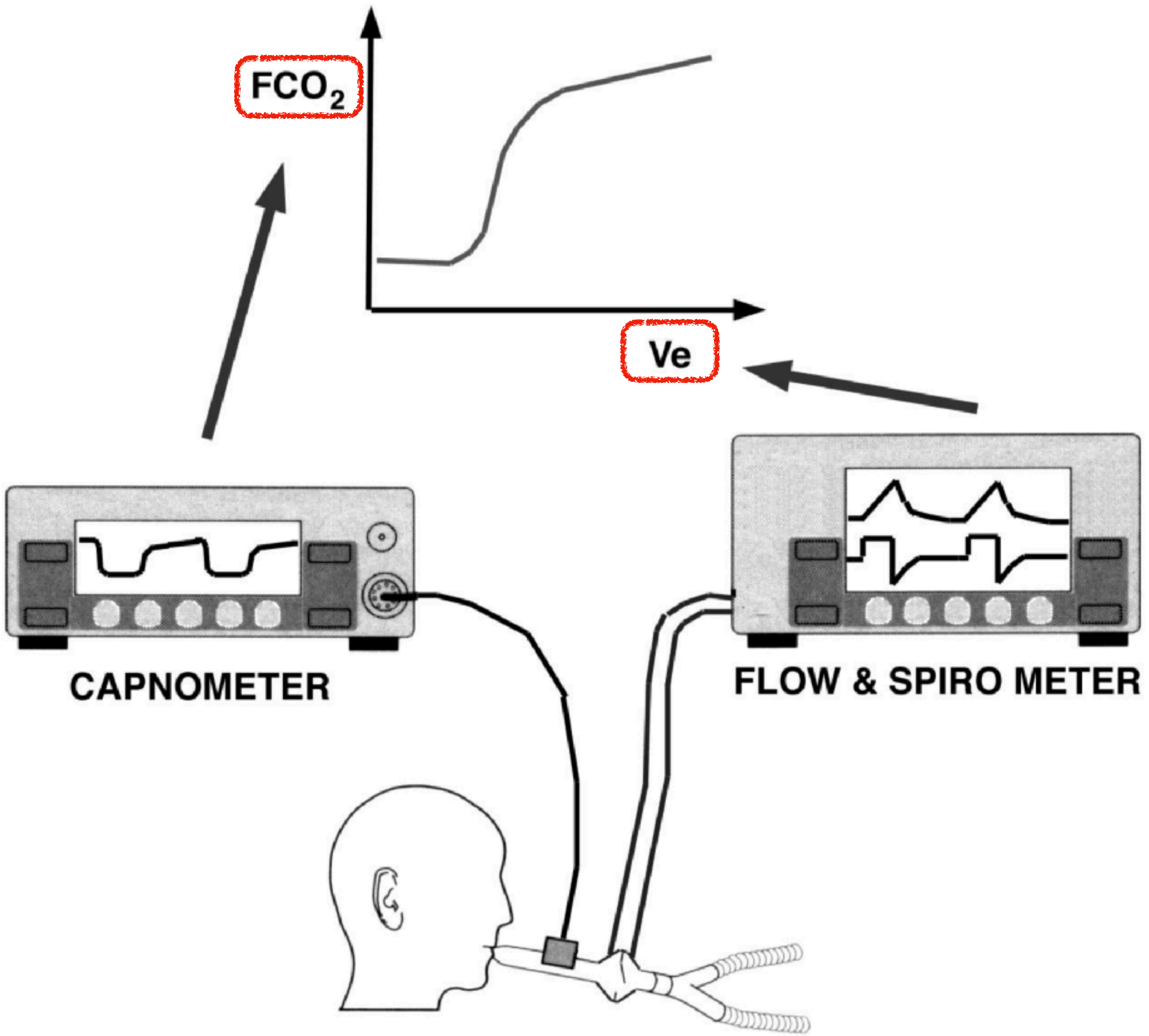
生理学を面白がれるか否か

通常のカプノグラフィー：横軸が時間

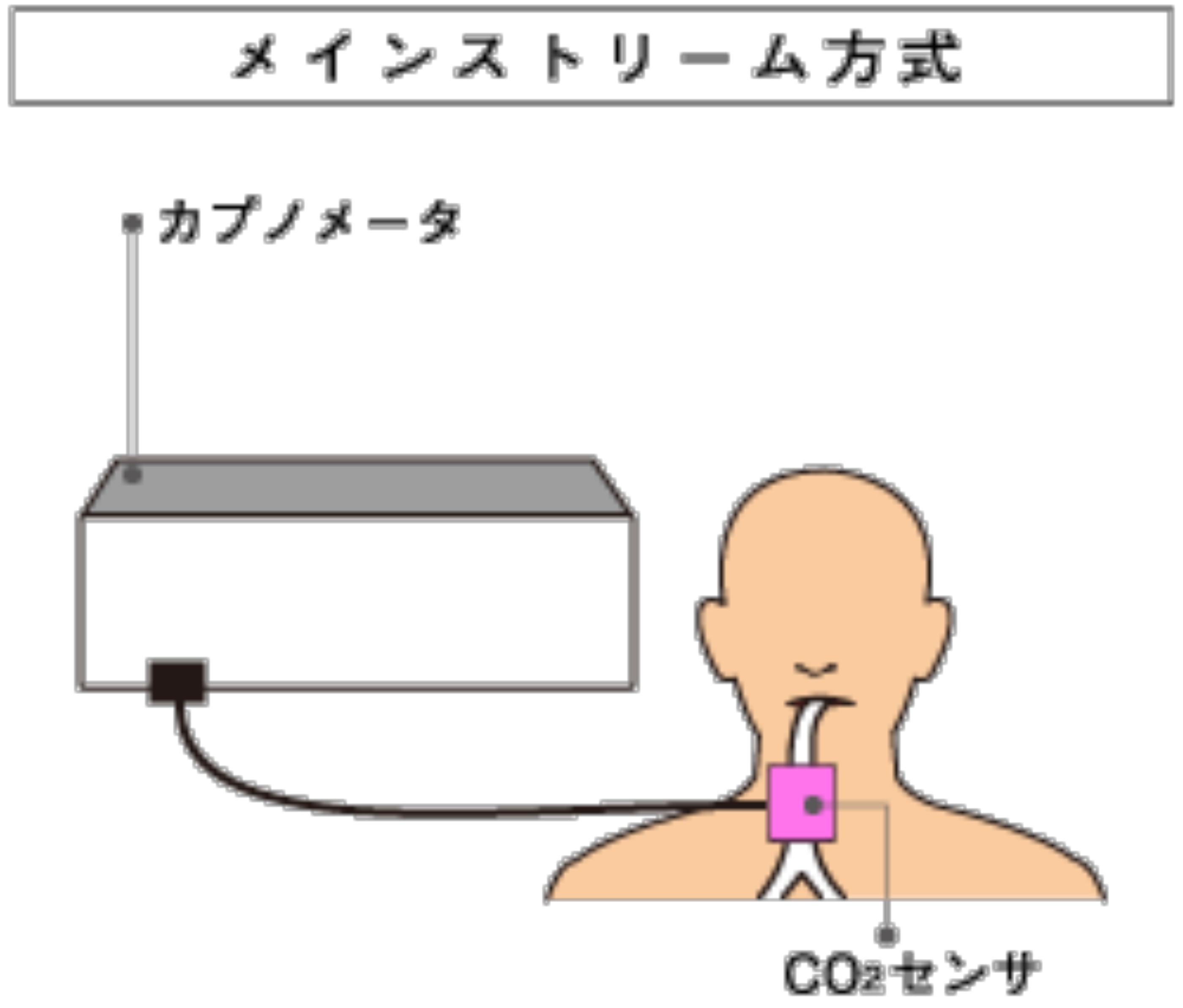


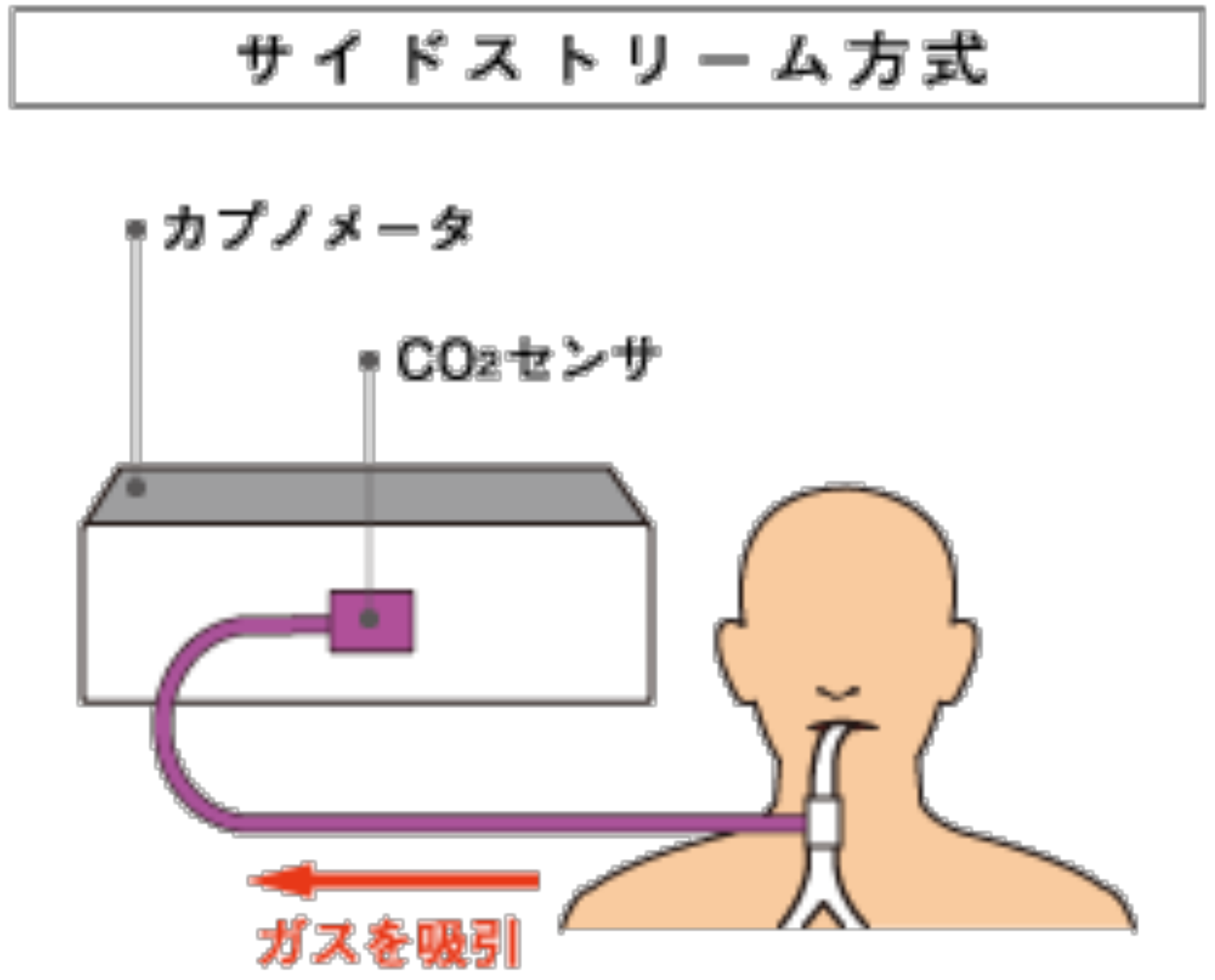
- 第I相：吸気の最後から呼気の初期。気管・気管・気管支など解剖学的死腔のガス。PCO_2は0mmHgを示す
- 第II相：肺胞ガスと解剖学的死腔ガスの混合ガス。PCO2は上昇。
- 第III相：肺胞からのガス排出。ほぼ平坦、呼気終了時の値が$PETCO_2$
- 第IV相：吸気が開始。急激に下降し、基線まで戻る。

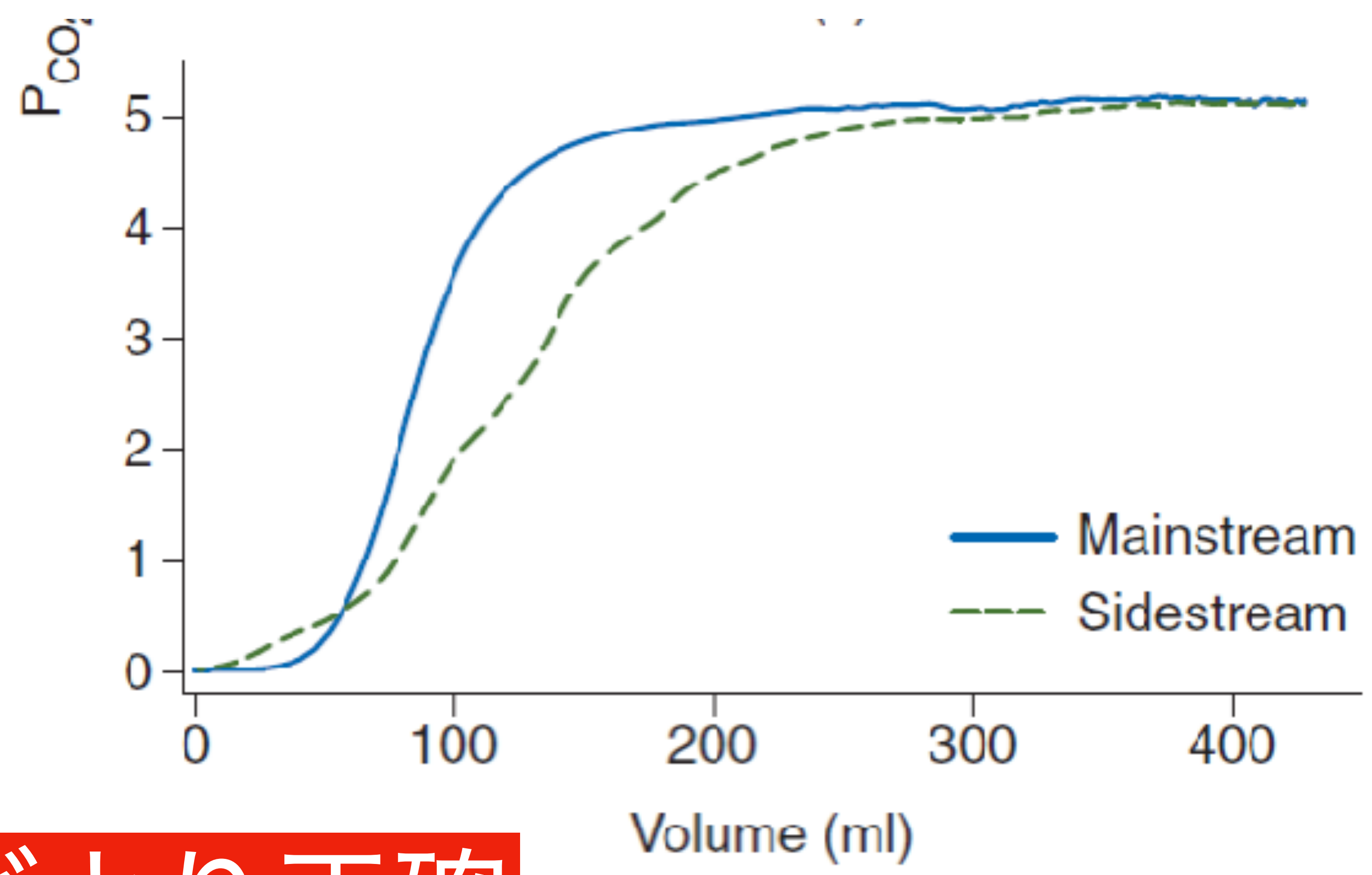
Volumetric capnography：横軸がヴォリューム



Capnography：方式



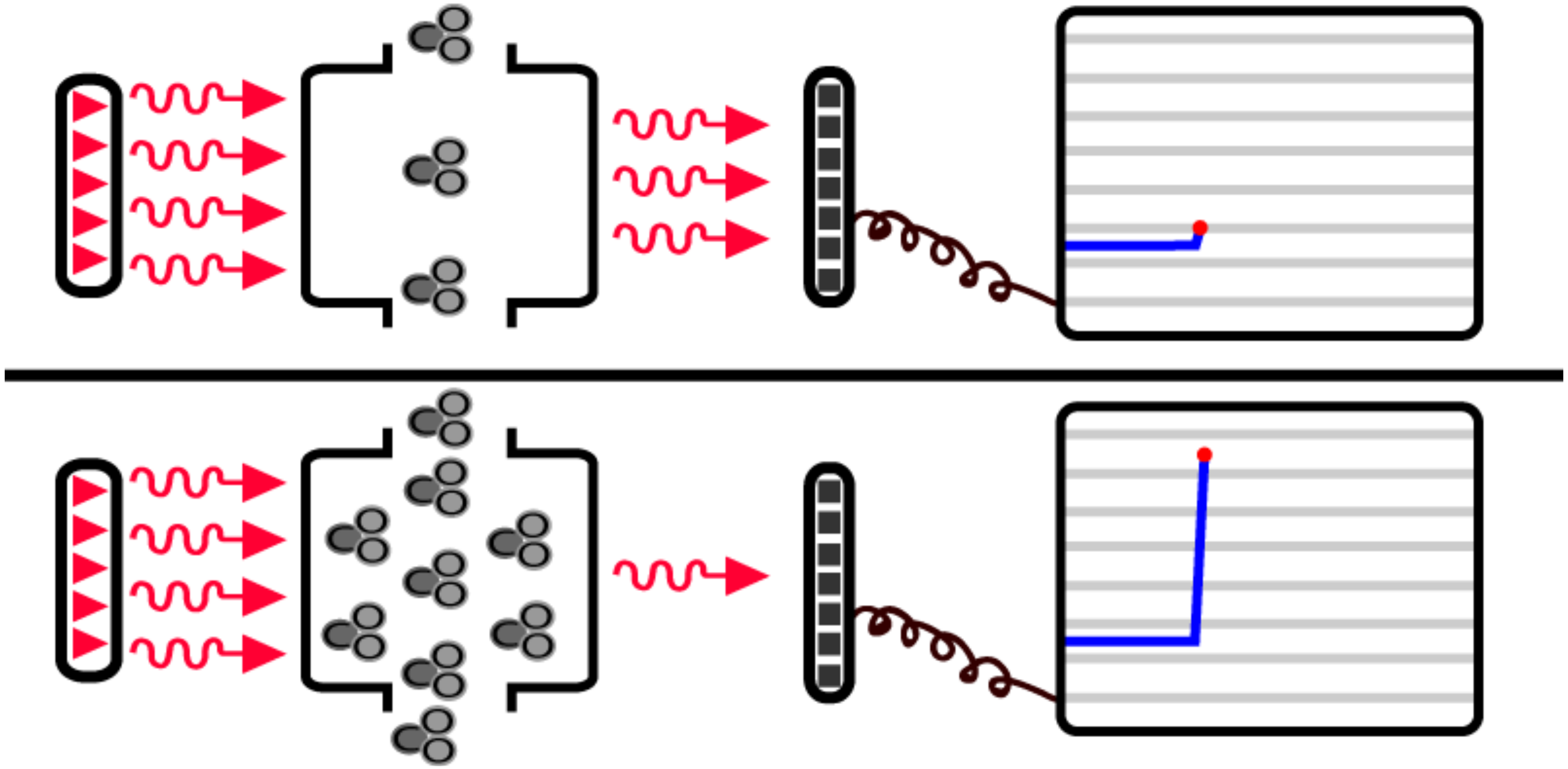




メインストリームの方がより正確

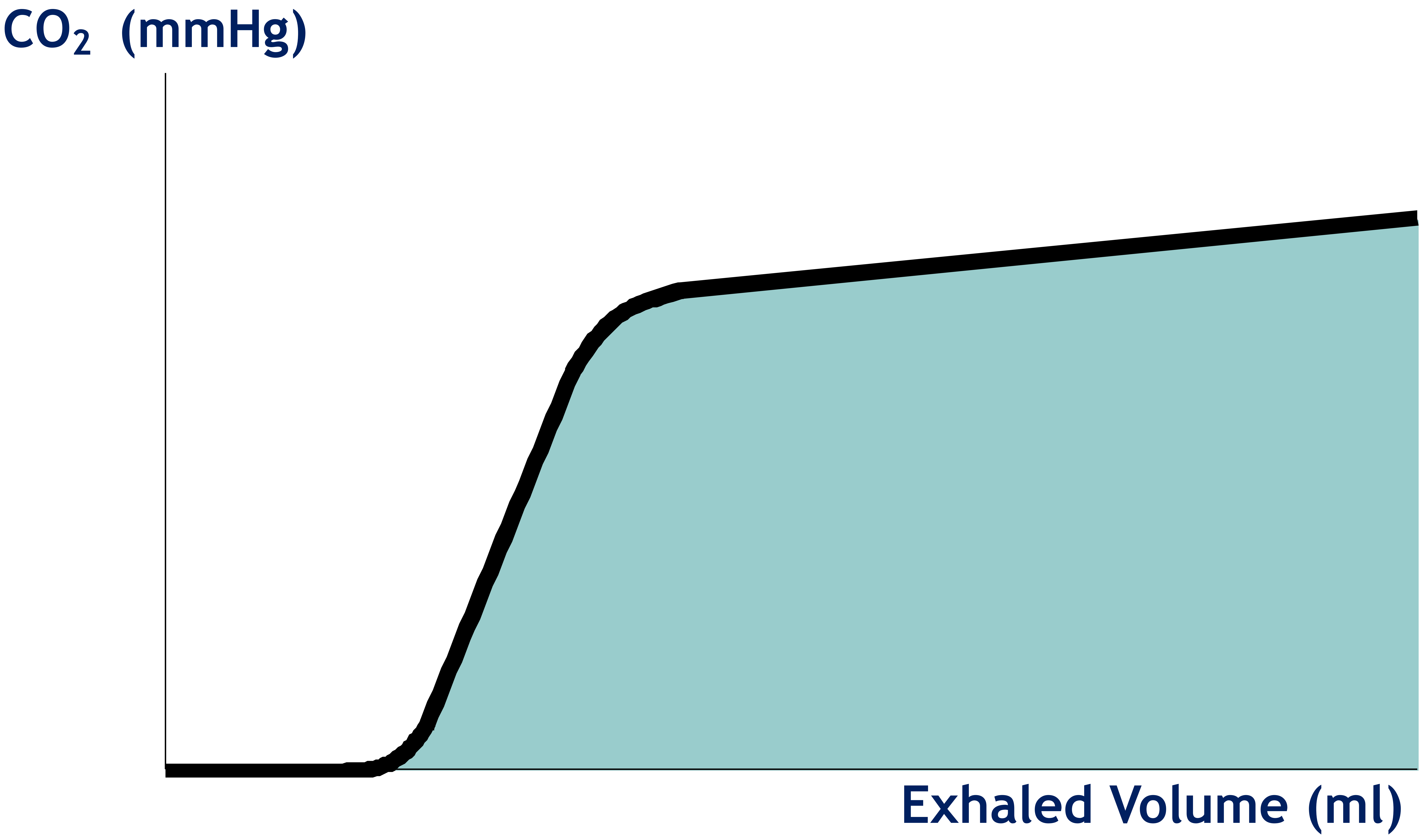
Balogh. BJA 2016

Capnography：原理

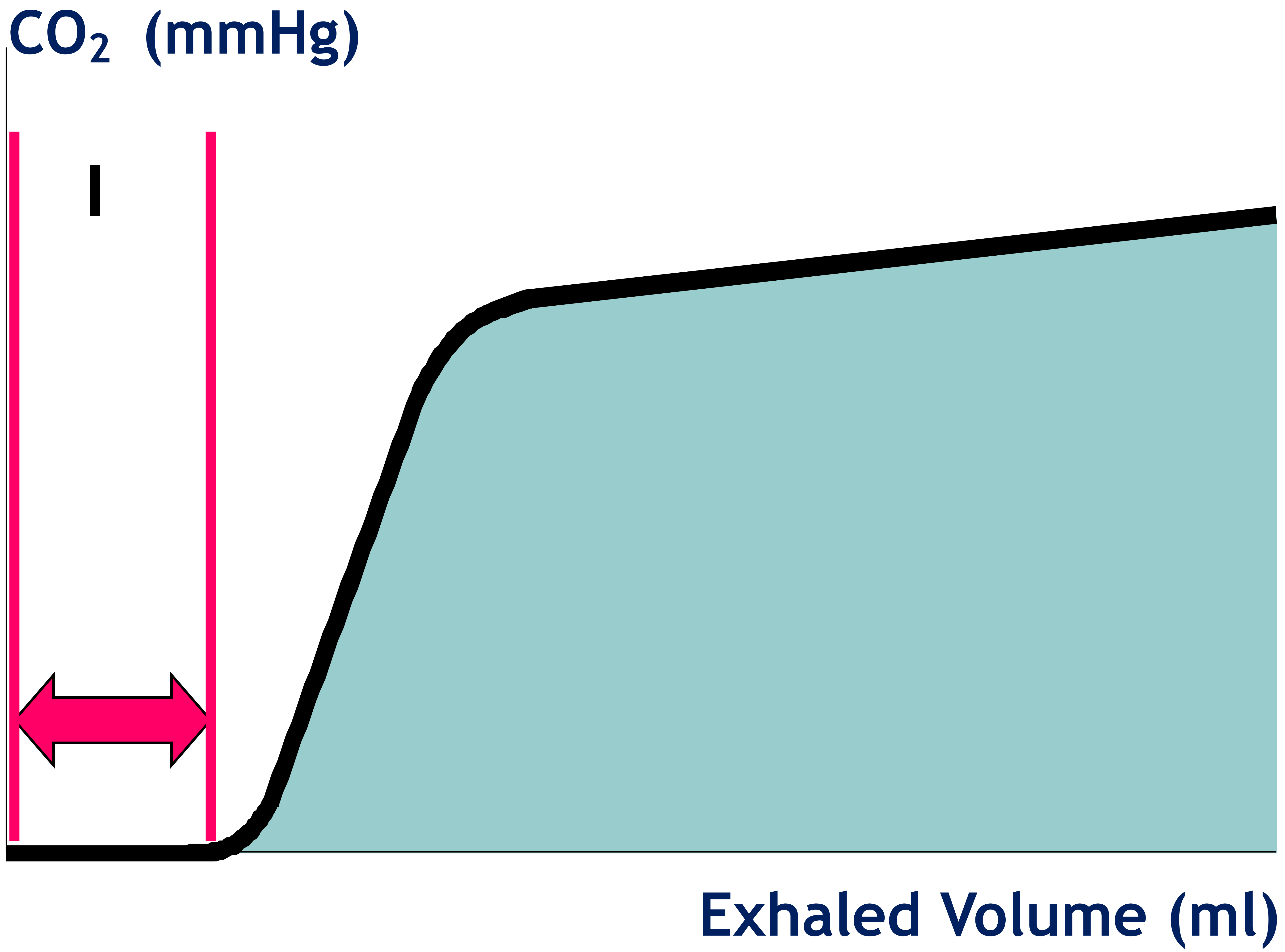


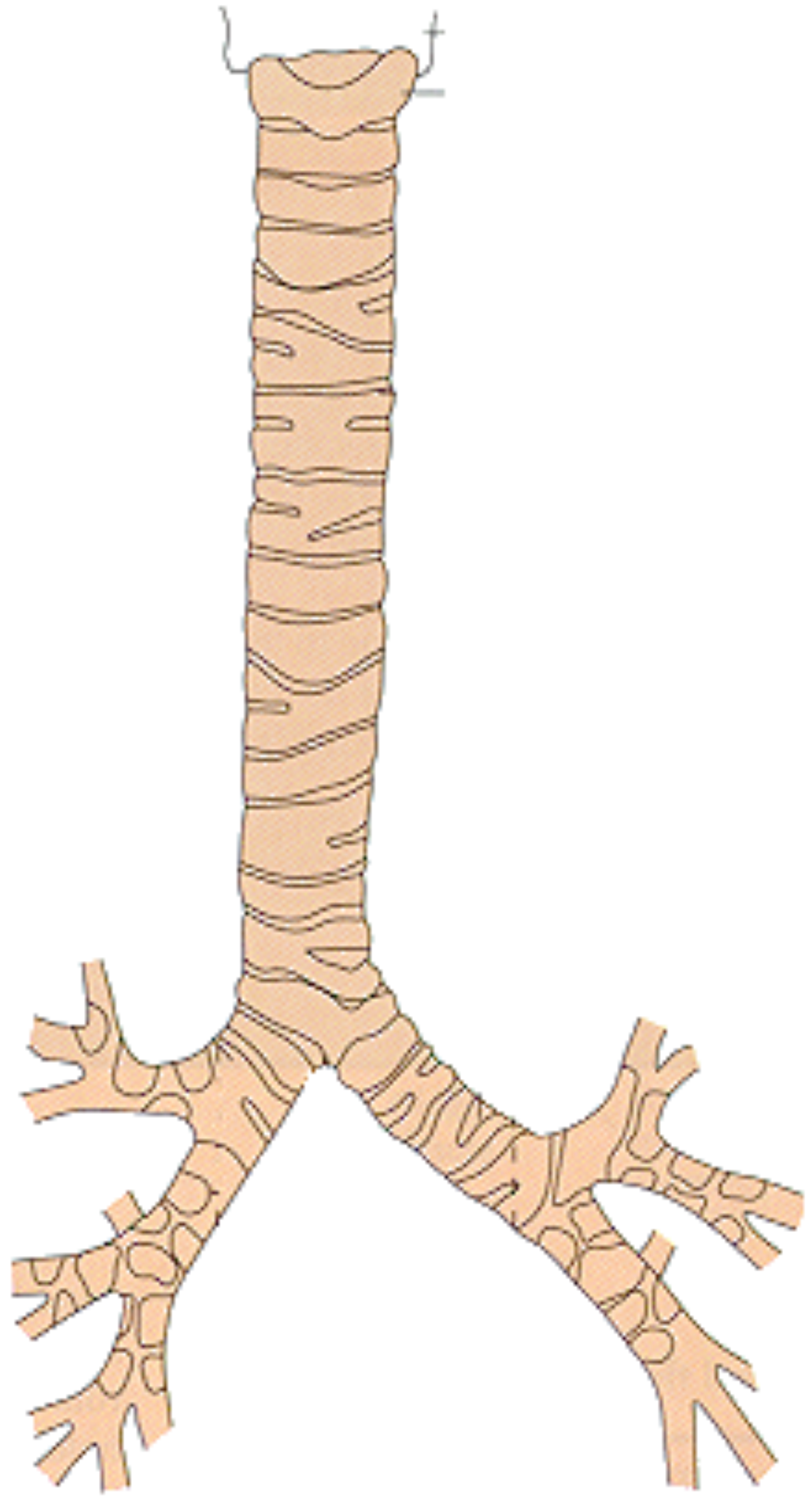
原理：CO2が赤外光を吸収

正常波形

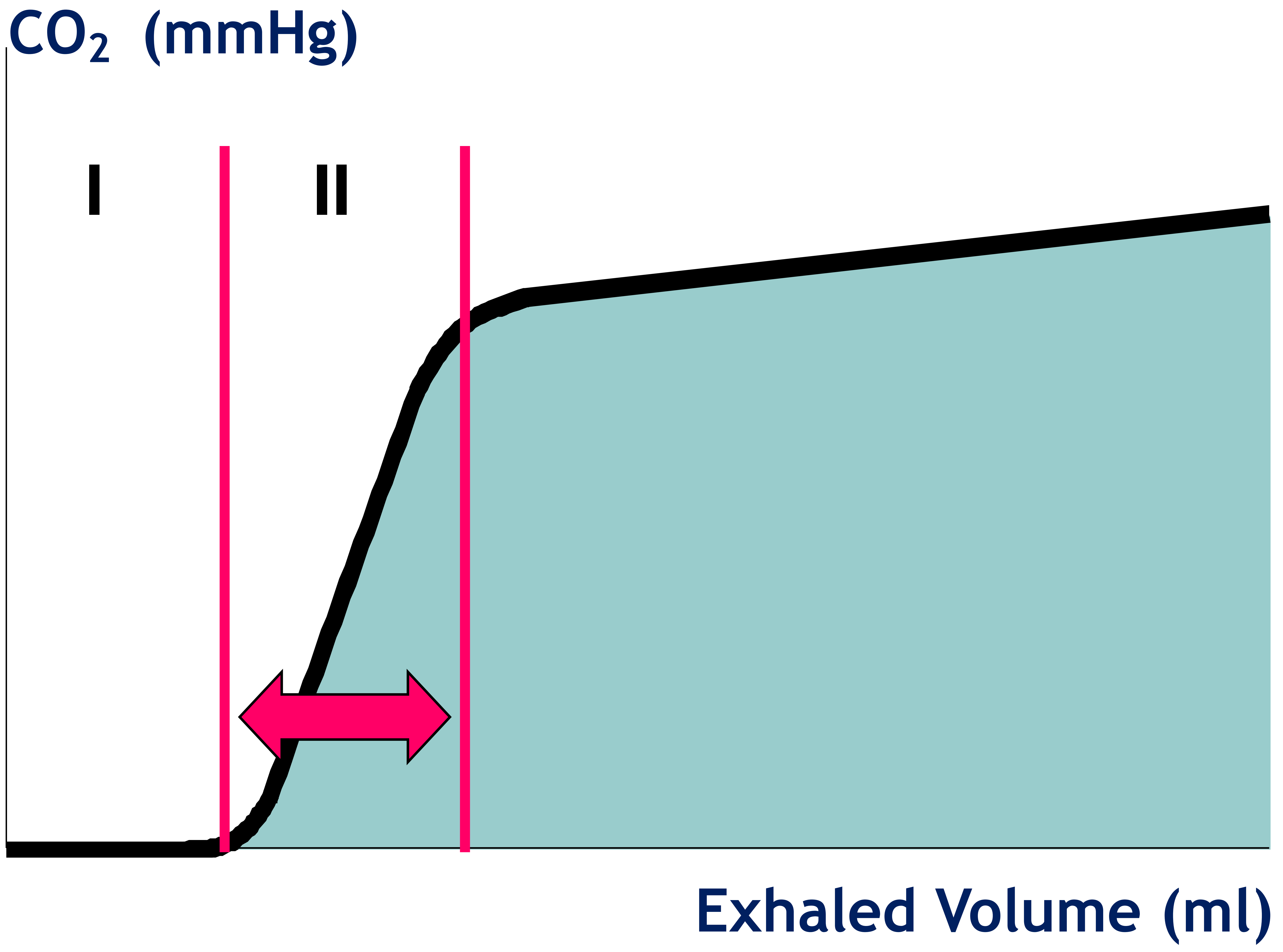


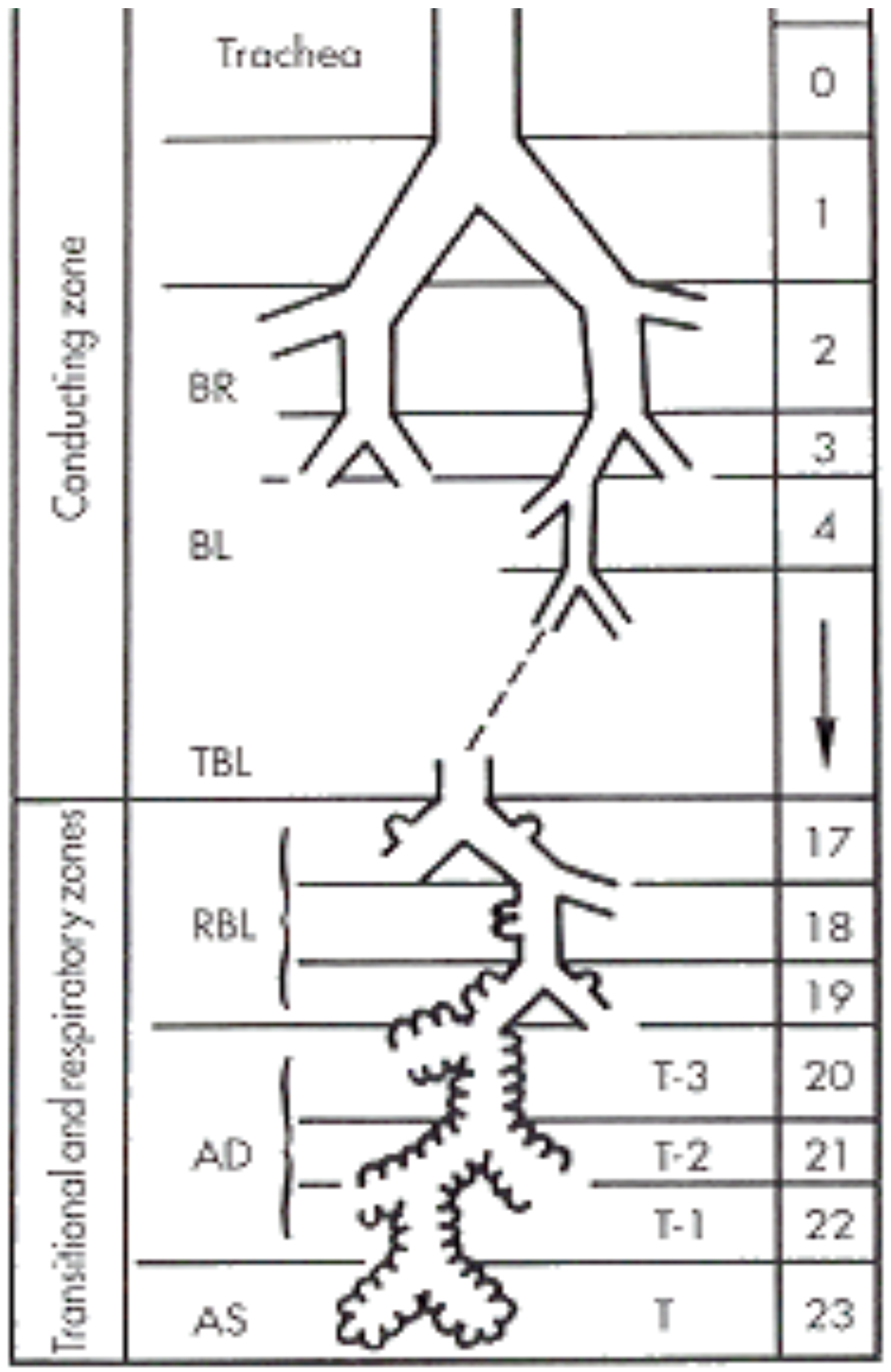
Phase I：気管チューブ・気管・気管支



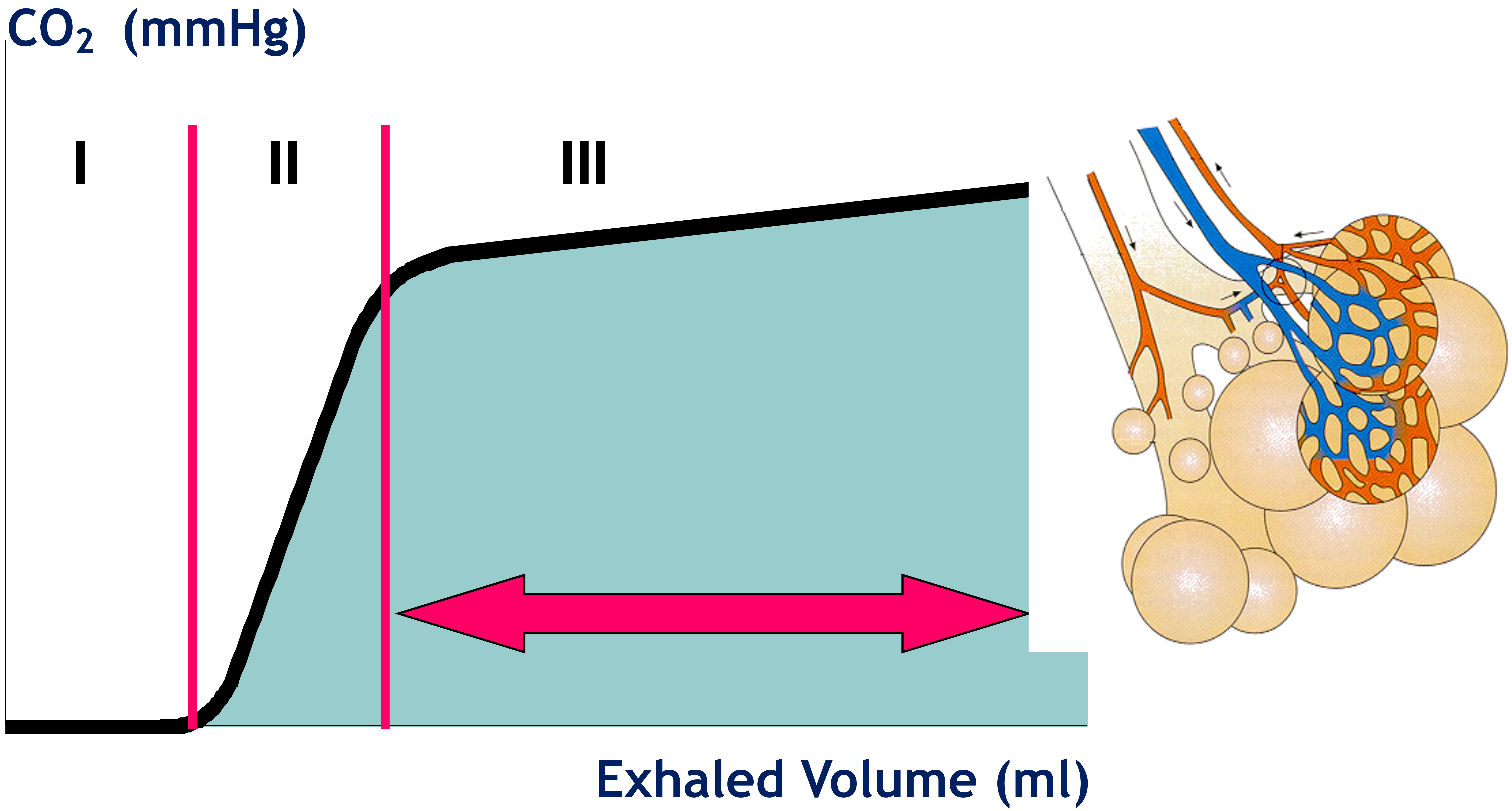


Phase II: 末梢気道からの混合ガス

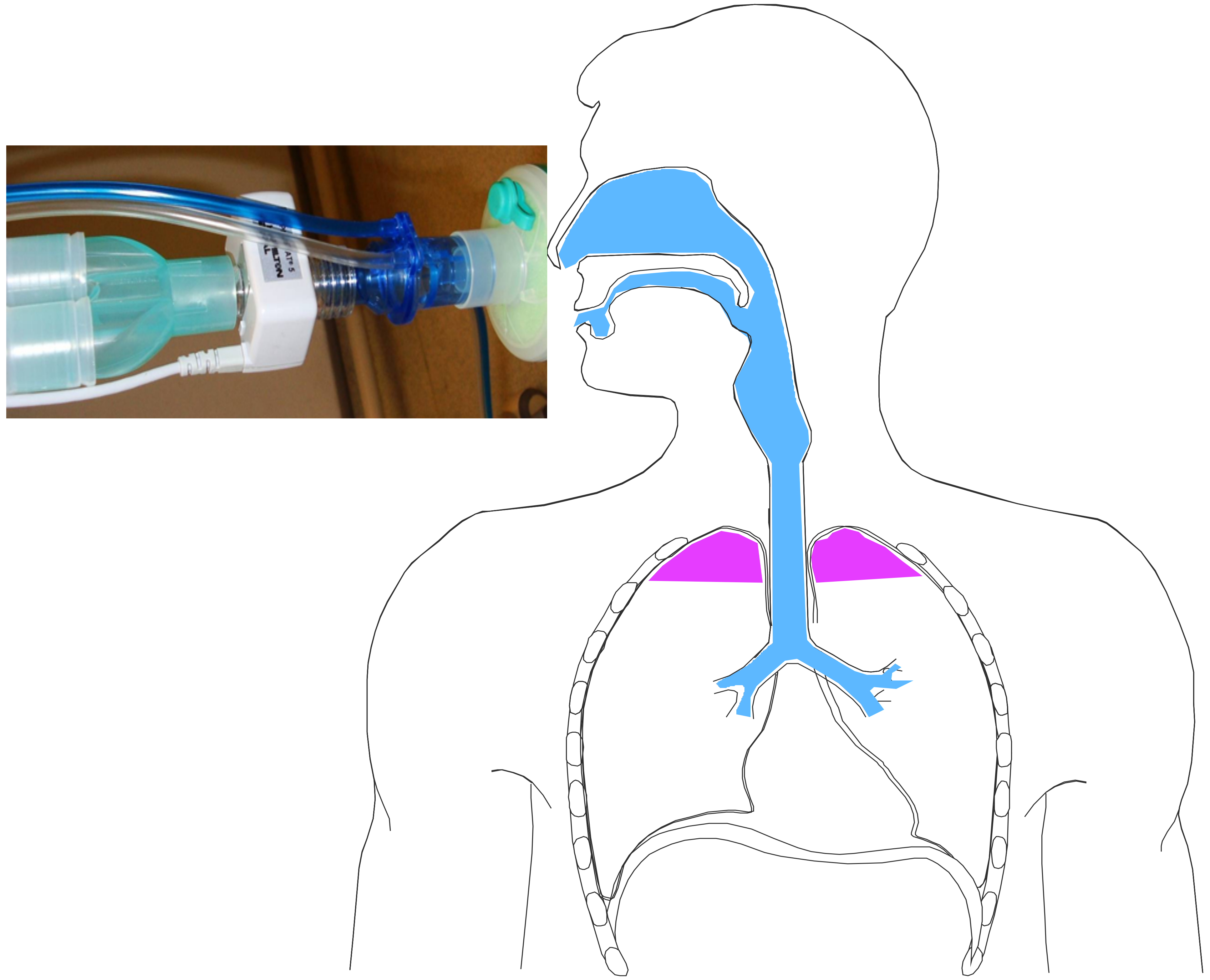


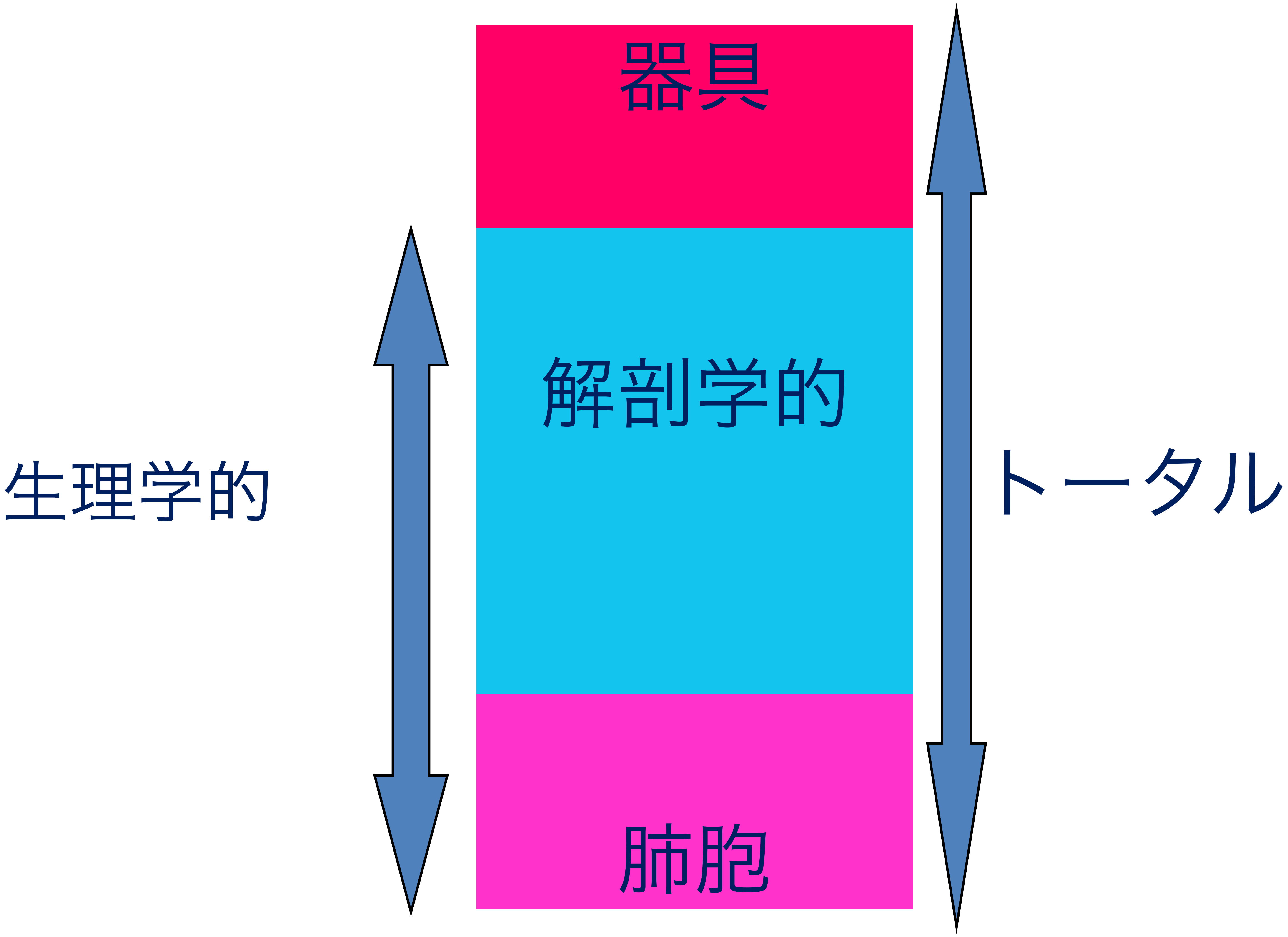


Phase III: 肺胞からのガス

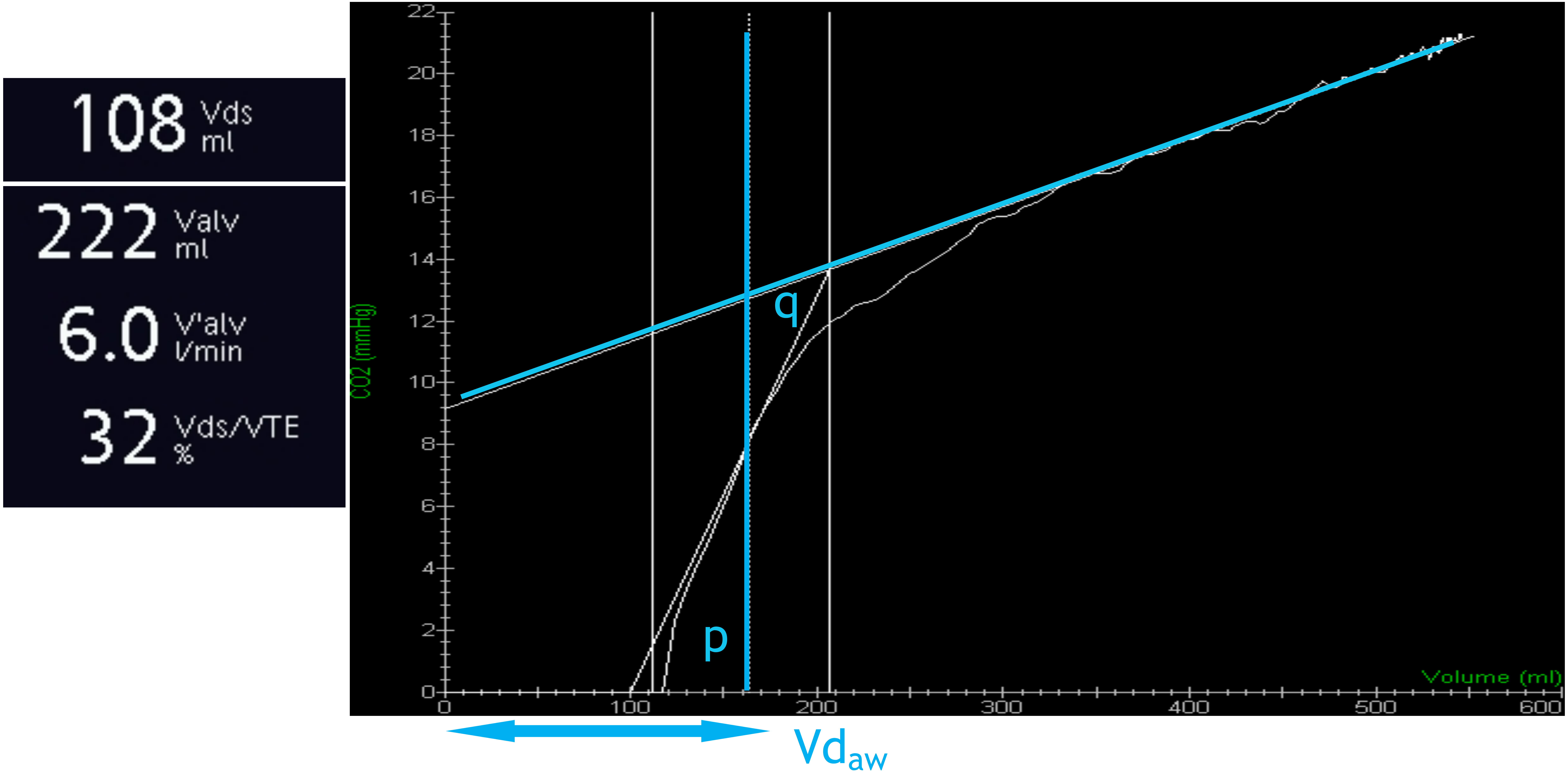


死腔：換気はあるが血流がない





解剖学的死腔


108 Vds ml
222 Valv ml
6.0 V'alv l/min
32 Vds/VTE %
CO2 (mmHg)
Volume (ml)
q
p
Vdaw

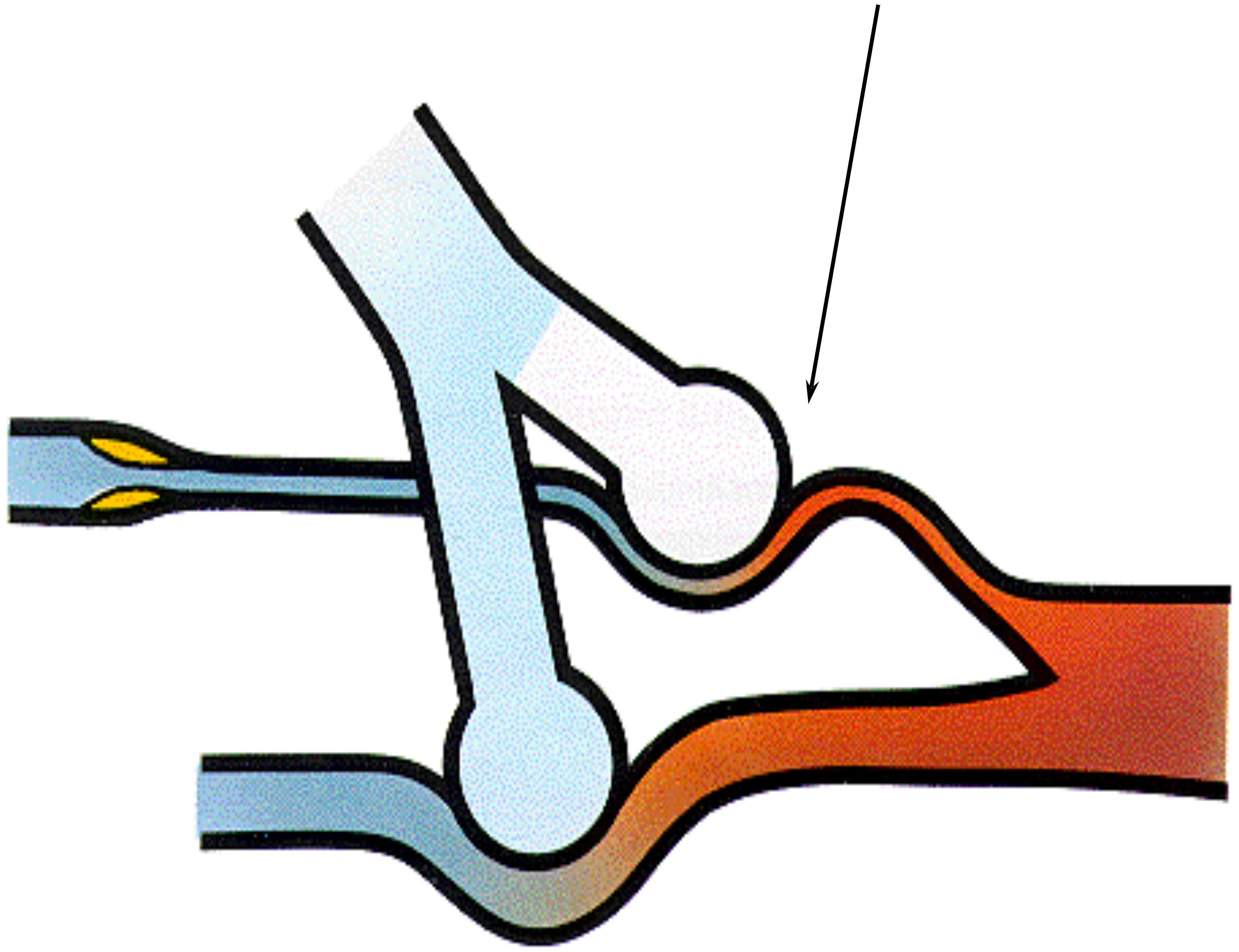
肺胞死腔

- 正常では無視しうる

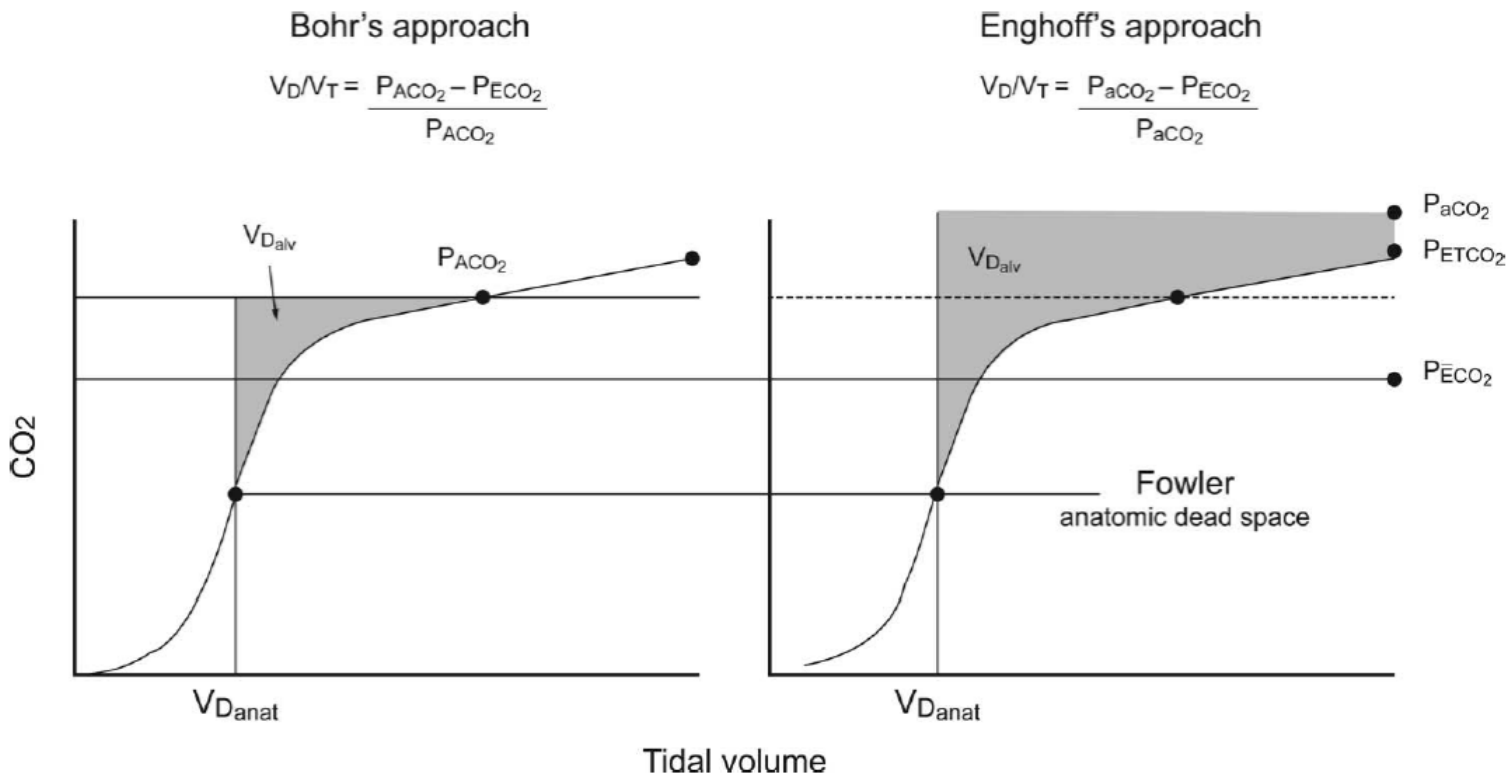
- 肺胞死腔増大

✓過肺胞の過膨張

✓V/Q ミスマッチ

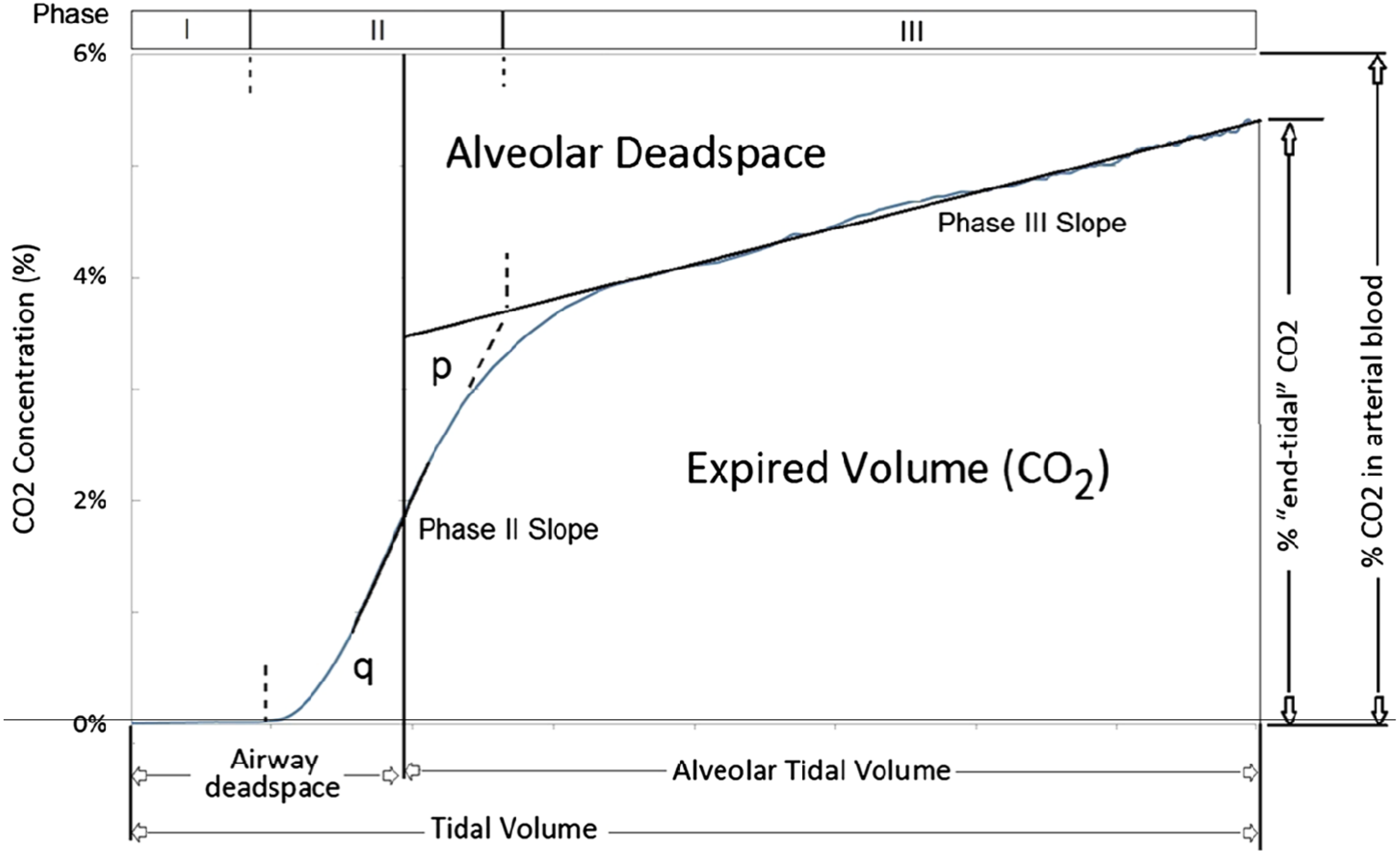


Alveolar dead space



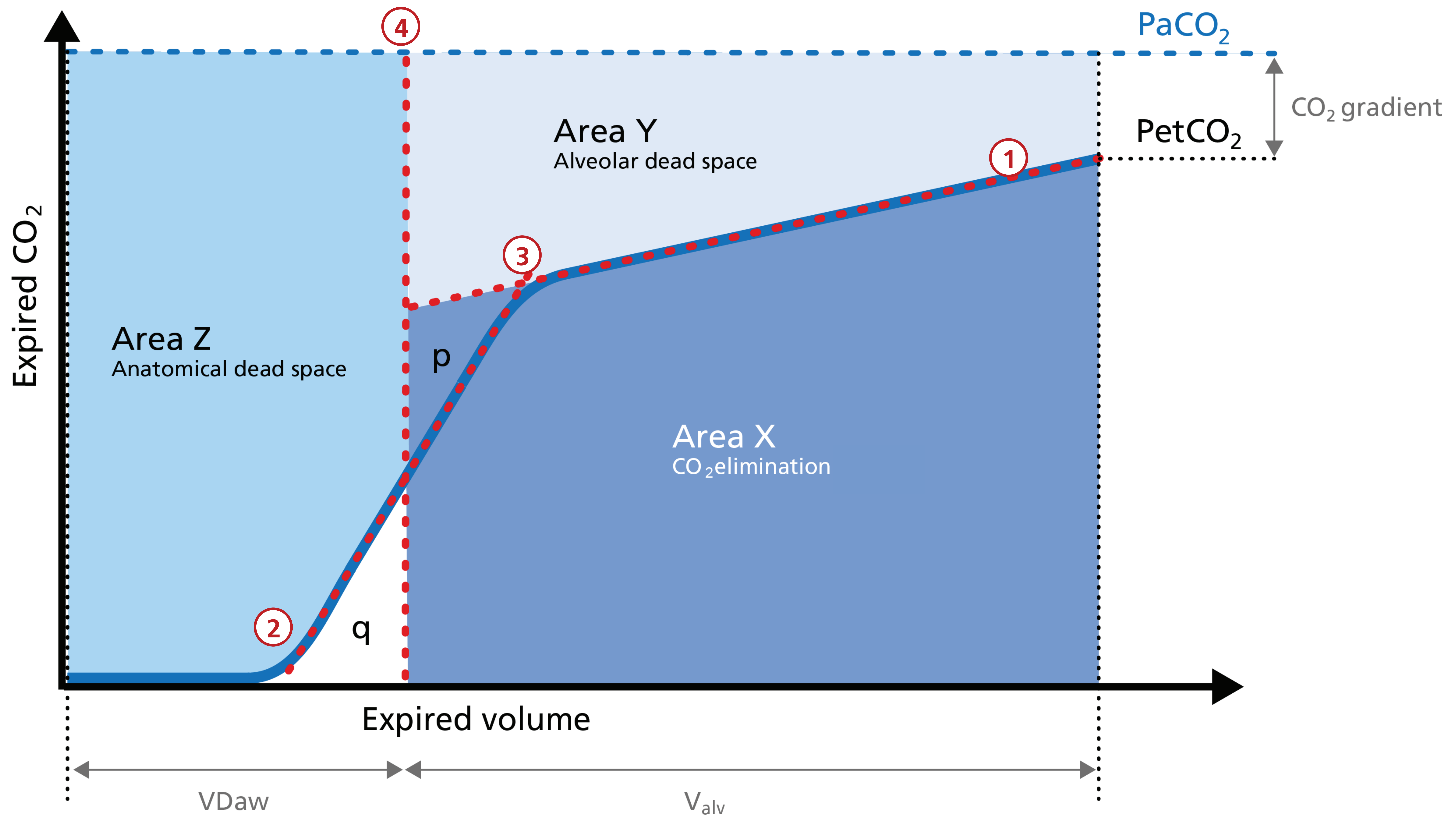
ゾーンで考える

23 VeCO2 ml
213 V'CO2 ml/min



Phase
I
II
III
6%
4%
2%
0%
CO2 Concentration (%)
Alveolar Deadspace
Phase III Slope
p
Expired Volume (CO_2)
Phase II Slope
q
% "end-tidal" CO2
% CO2 in arterial blood
Airway deadspace
Alveolar Tidal Volume
Tidal Volume

ゾーンで考える

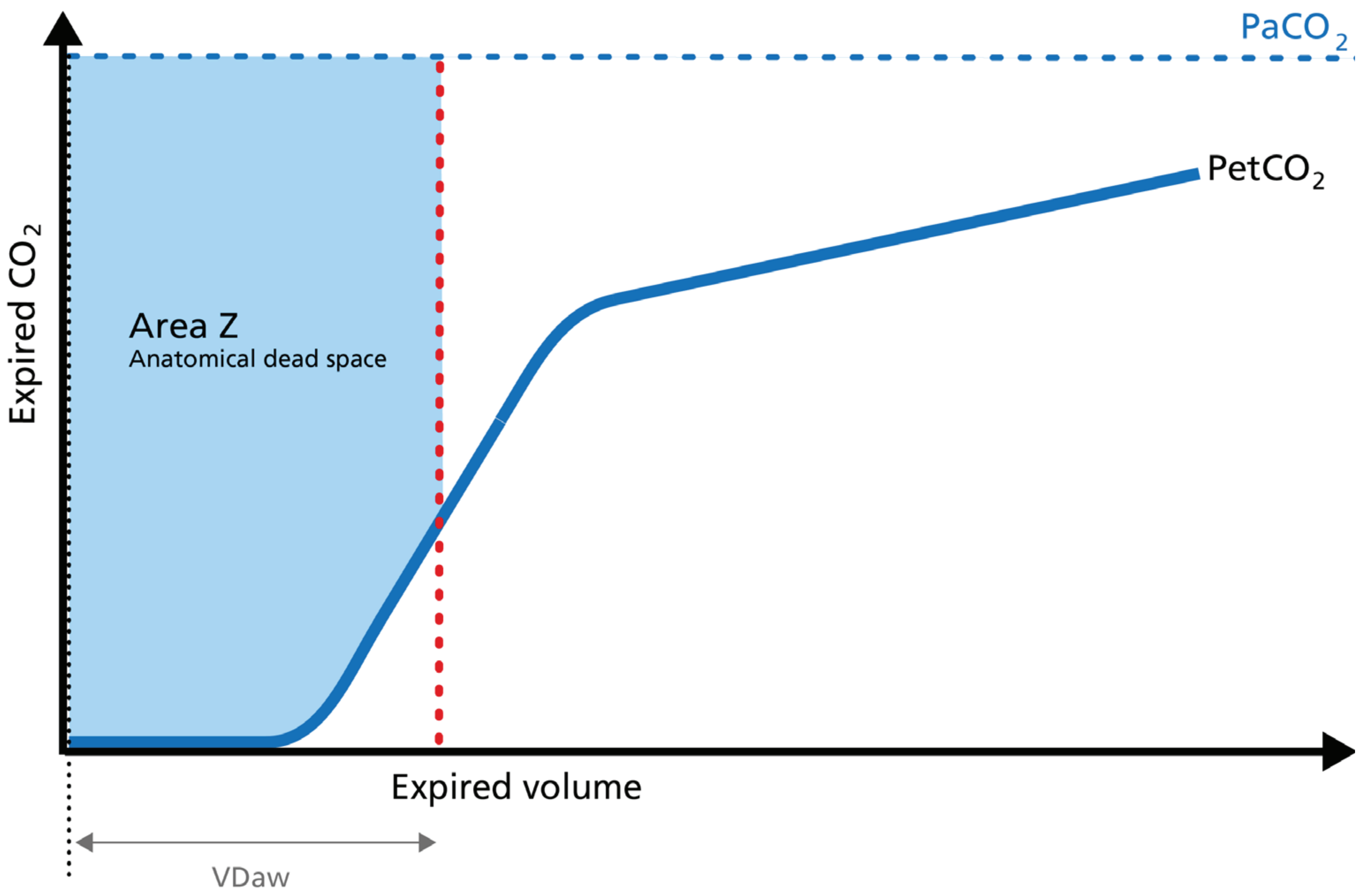

4
$PaCO_2$
CO_2 gradient
$PetCO_2$
Area Y
Alveolar dead space
1
3
Expired CO_2
Area Z
Anatomical dead space
p
Area X
CO_2 elimination
2
q
Expired volume
VDaw
V_{alv}

解剖学的死腔：VDaw

- 解剖学的死腔↑：人工的な死腔を追加、過剰なPEEP

An expansion of Area Z can indicate an increase in anatomical dead space ventilation (VD_{aw}). Consider a reduction of your artificial dead space volume.

A **diminution of Area Z** is seen when artificial dead space volume is decreased and when excessive PEEP is decreased.



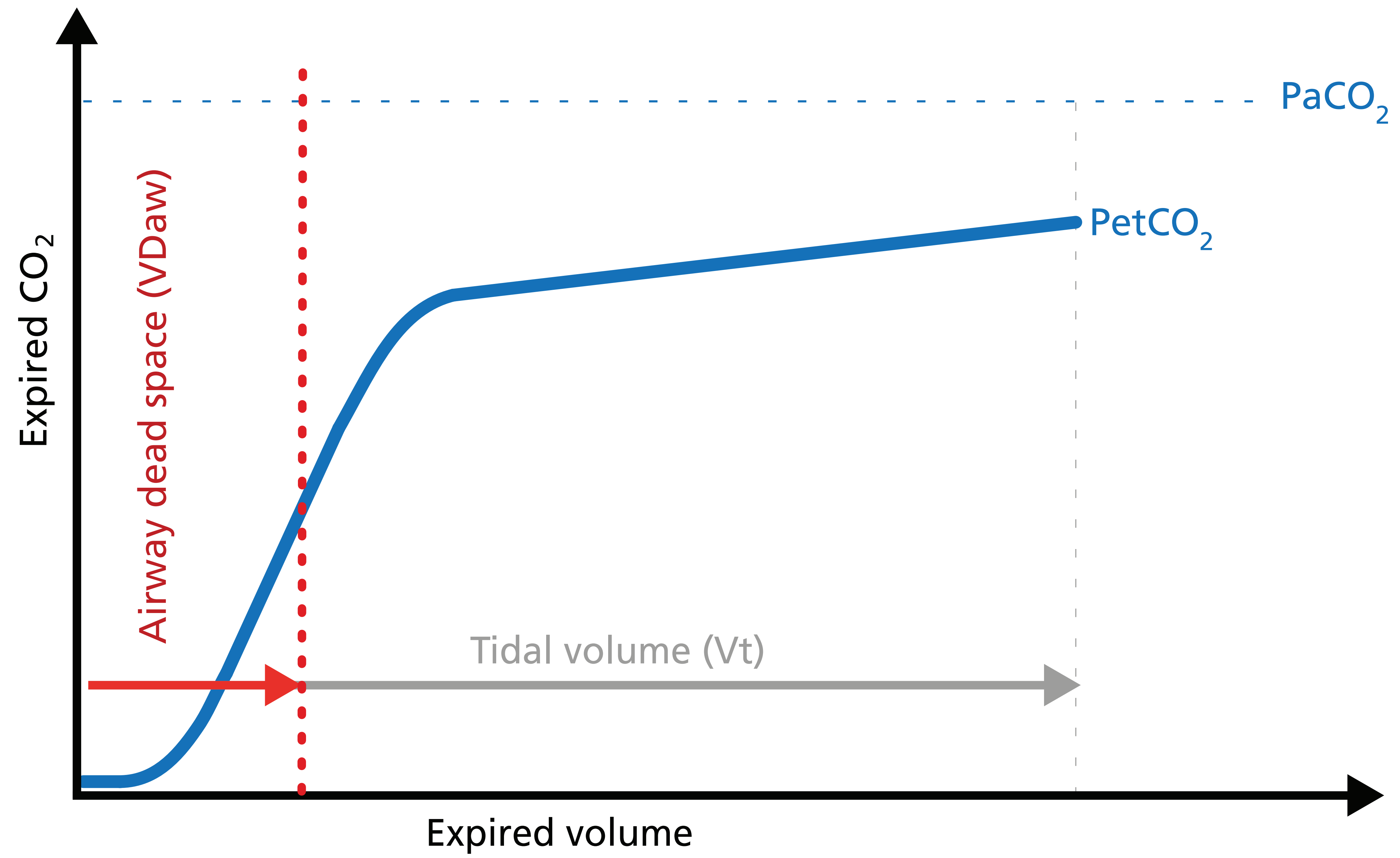
死腔換気率：VDaw/Vte

- 正常値：25-30%
- 死腔換気率↑：ARDSなど（VDaw/Vte = 60-80%）

A rising VD_{aw}/Vte ratio can be a sign of ARDS.

In a normal lung, the VD_{aw}/Vte ratio is between 25% and 30%.

In early ARDS, it is between 58% and up to 83%.

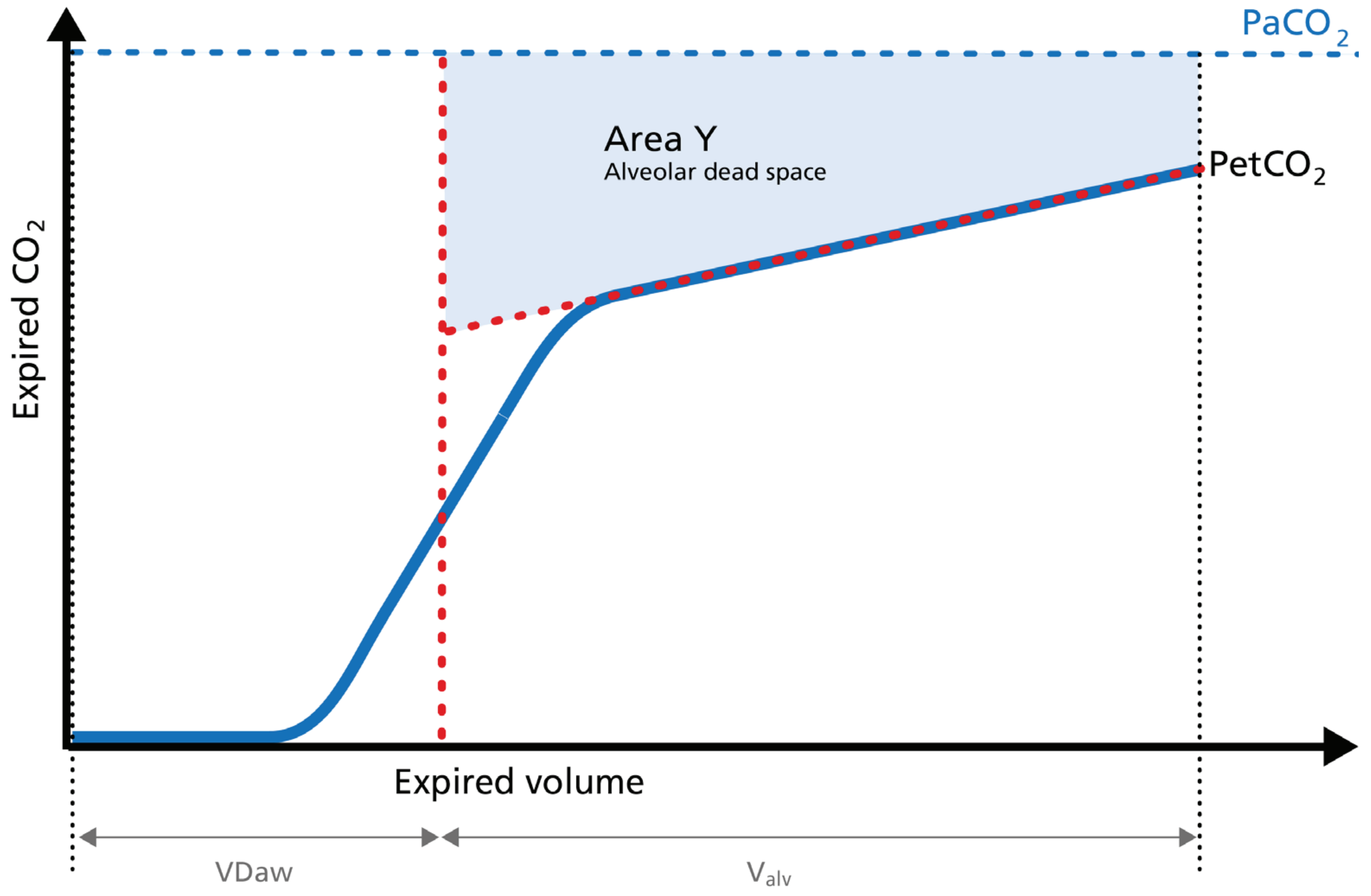


肺胞死腔

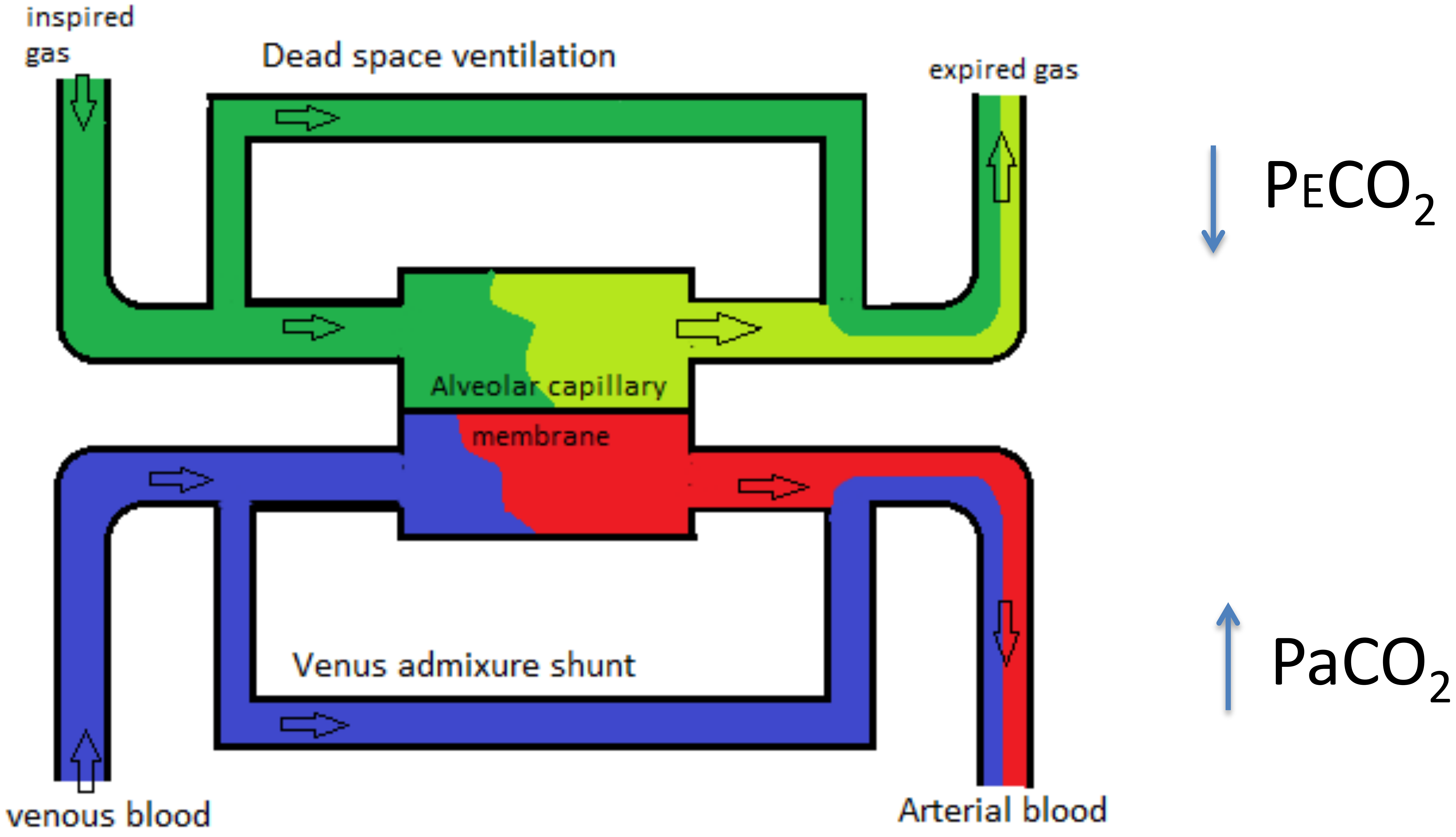
- ゾーンY：肺胞死腔のために呼出できないCO2
- 増加：COPD、肺過膨張、肺塞栓、肺高血圧、心拍出量低下

Increase
Alveolar dead space is increased in cases of lung emphysema, lung overdistension, pulmonary embolism, pulmonary hyper-tension, and cardiac output compromise.

Decrease
If the above mentioned conditions improve due to successful therapy, the alveolar dead space decreases.

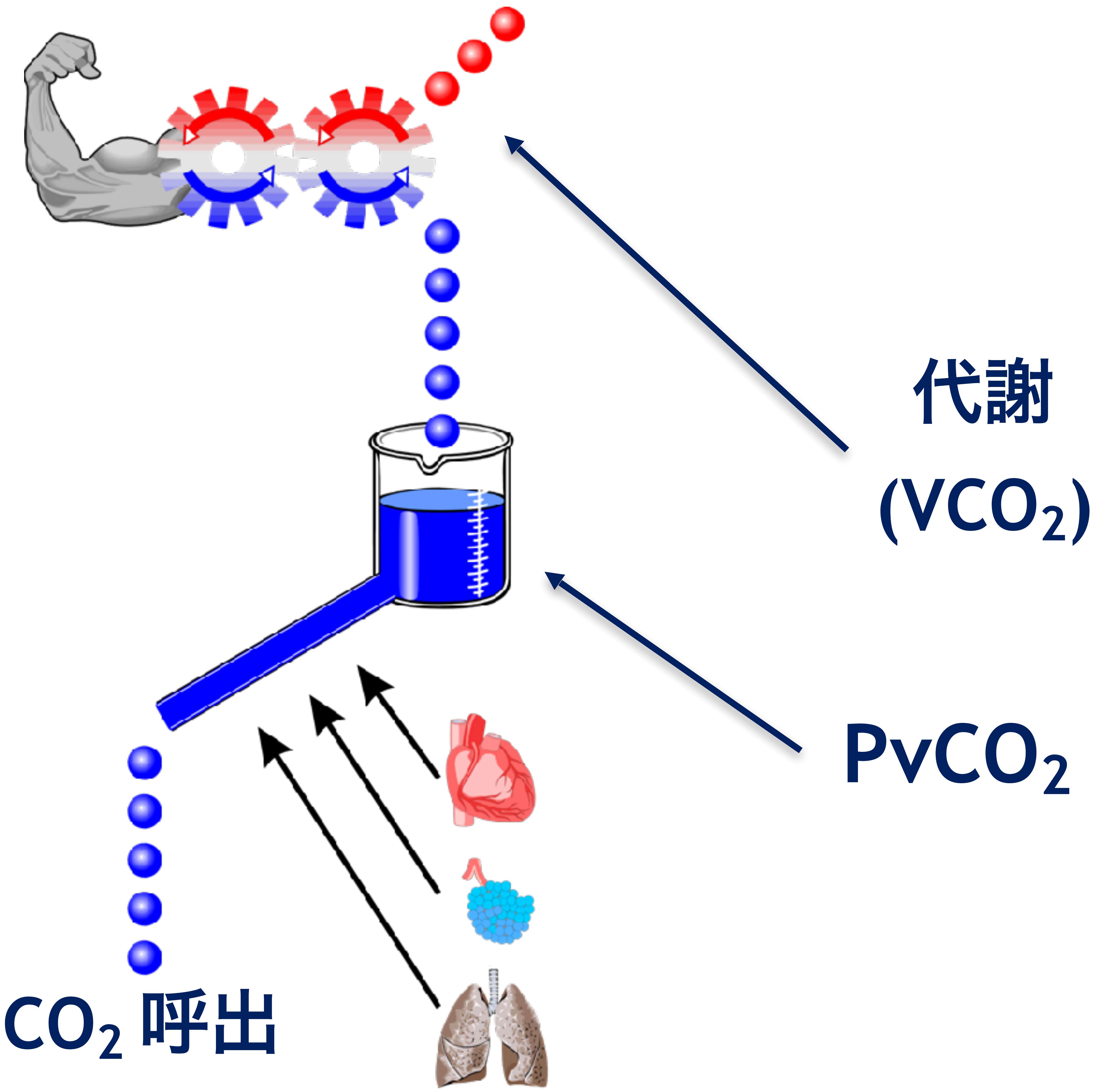


肺胞死腔↑・シャント↑→PaCO2とPeCO2の差が拡大

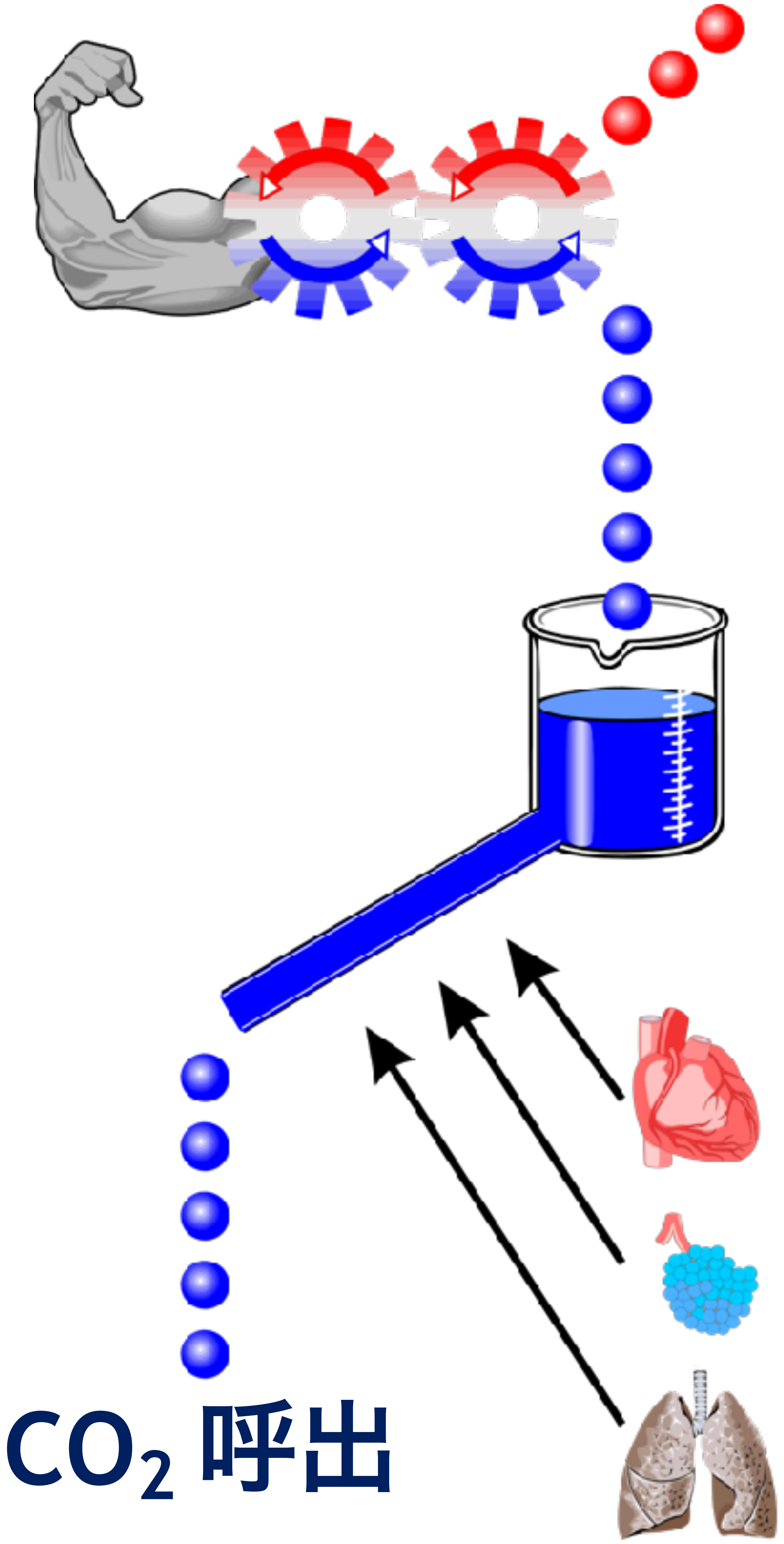


Both dead space and Shunt increase $PaCO_2$– $expCO_2$ difference

CO2の産生から呼出まで



CO2の産生から呼出まで



代謝

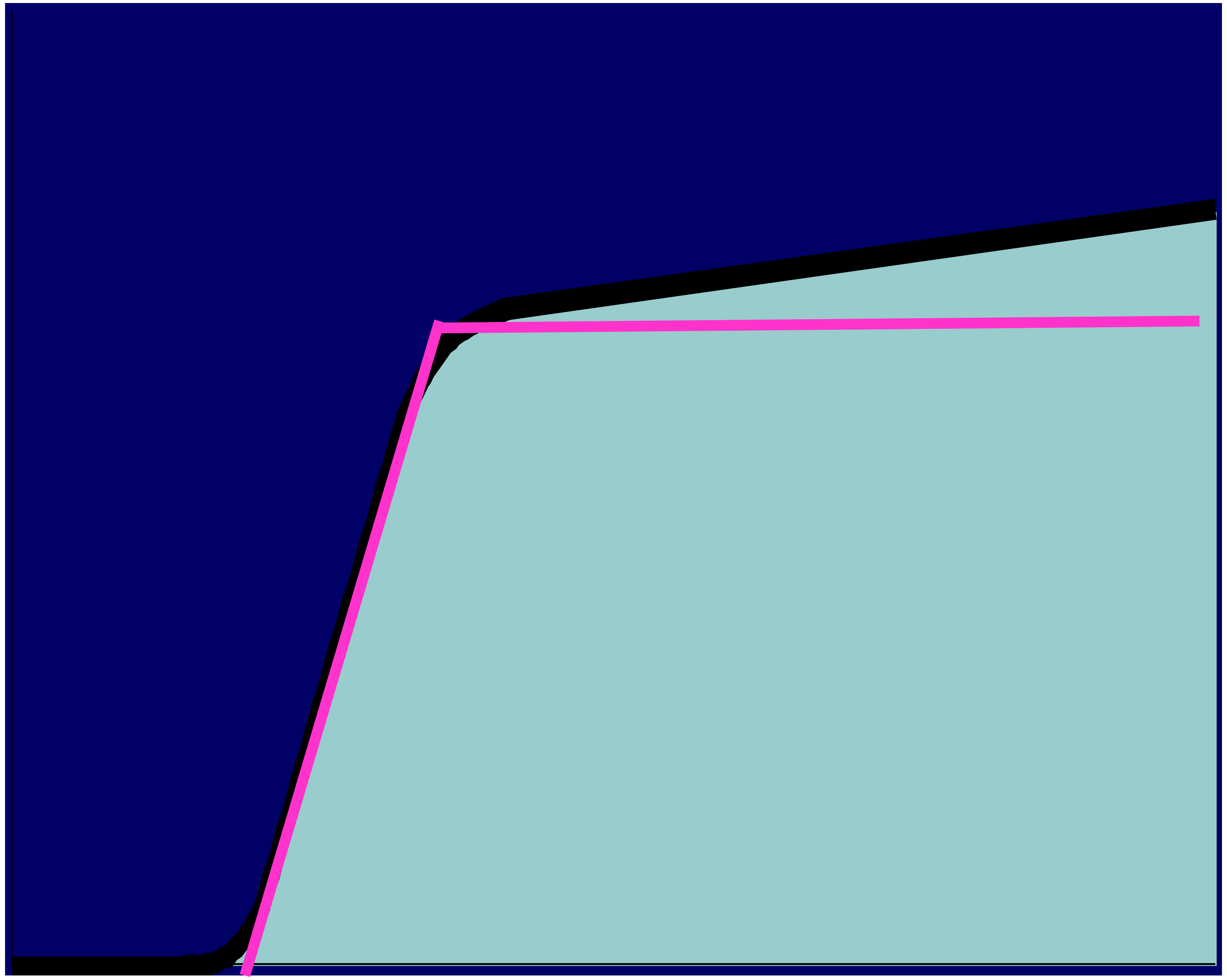
循環

拡散

換気

Phase II

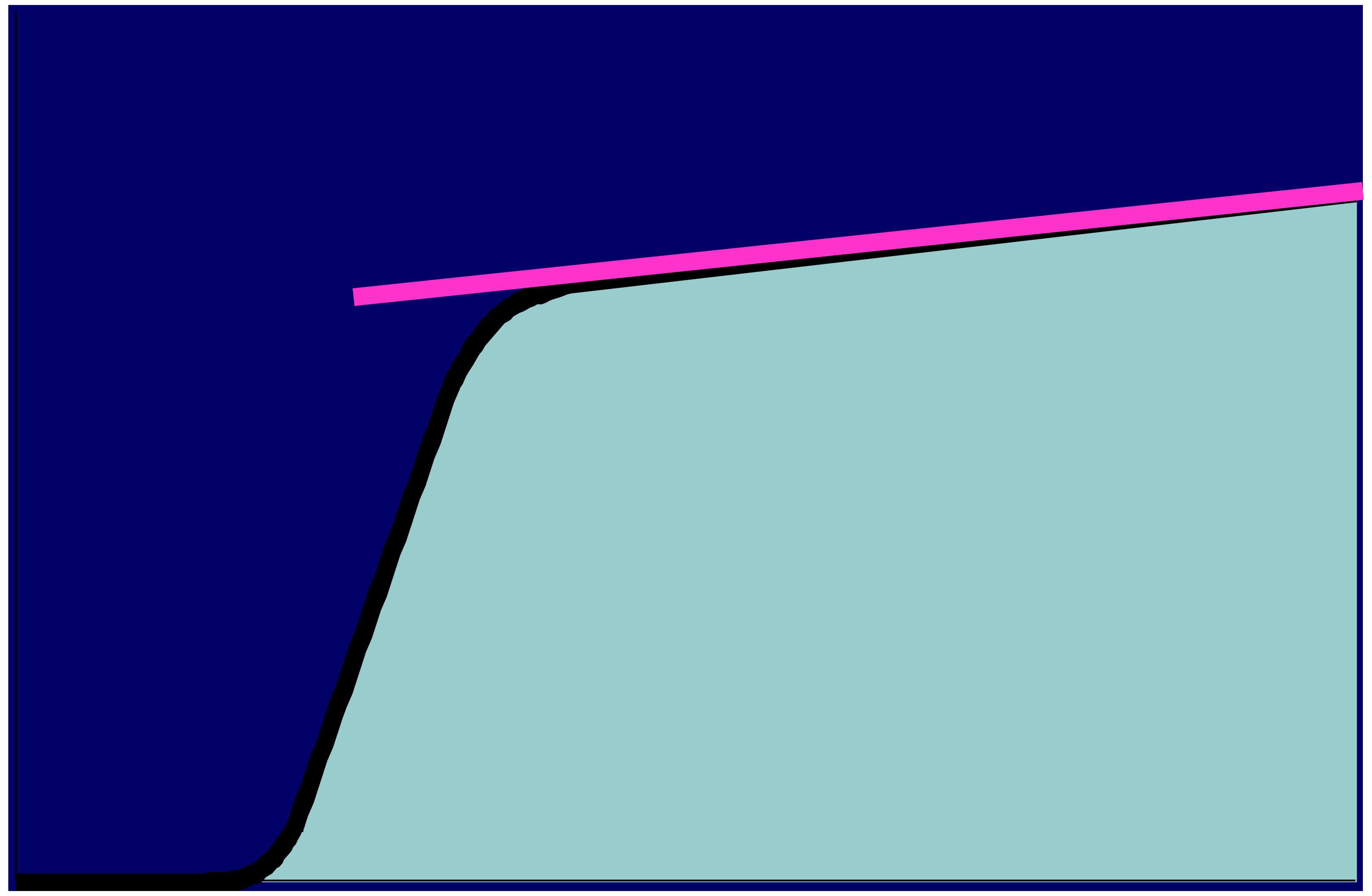
- 高さ: 循環、心拍出量
- 傾き: 気道抵抗

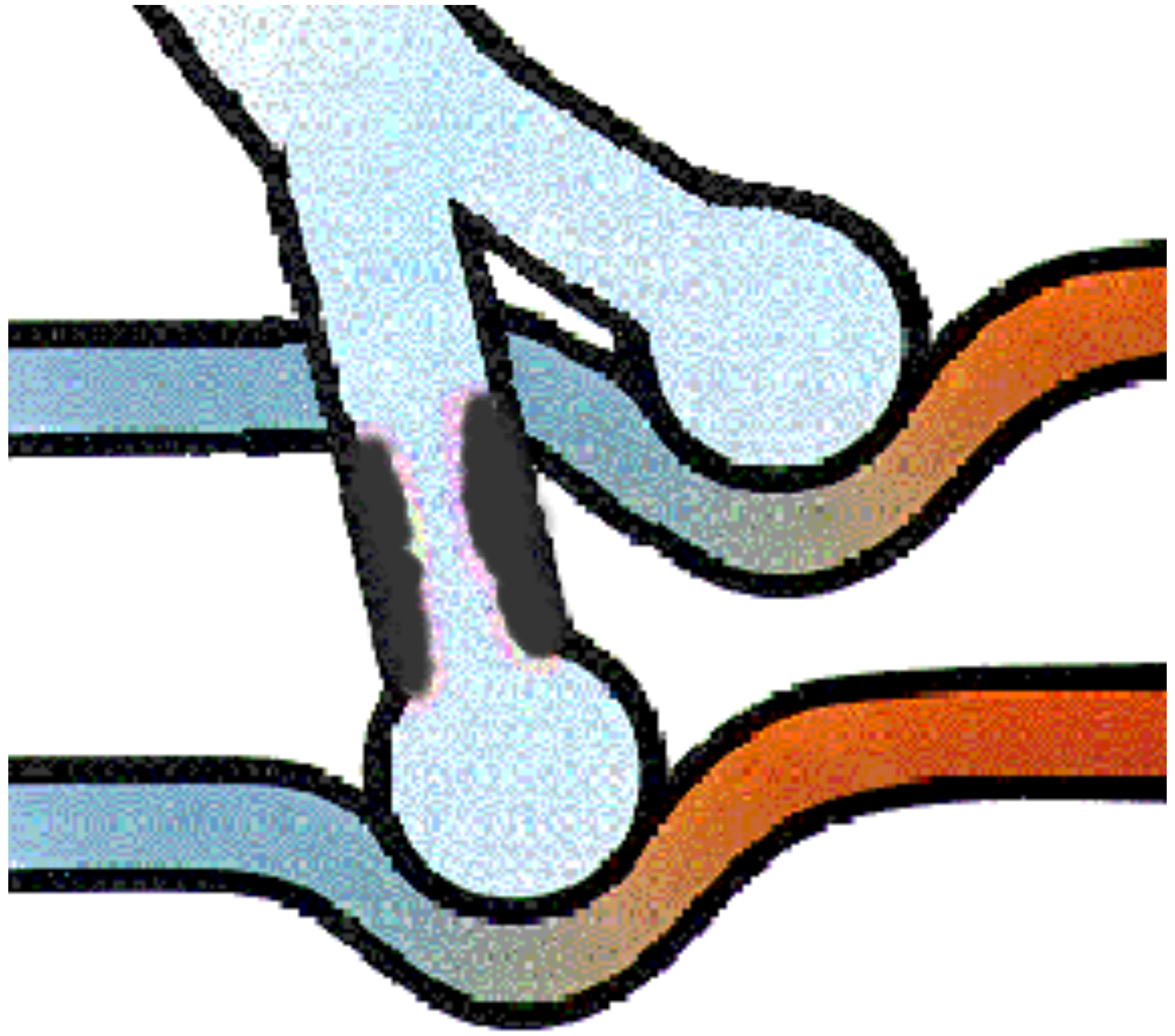


Phase IIIの傾き

肺の異質性を反映

- 閉塞がある肺胞は
  - CO_2は高い
  - 時定数が長い

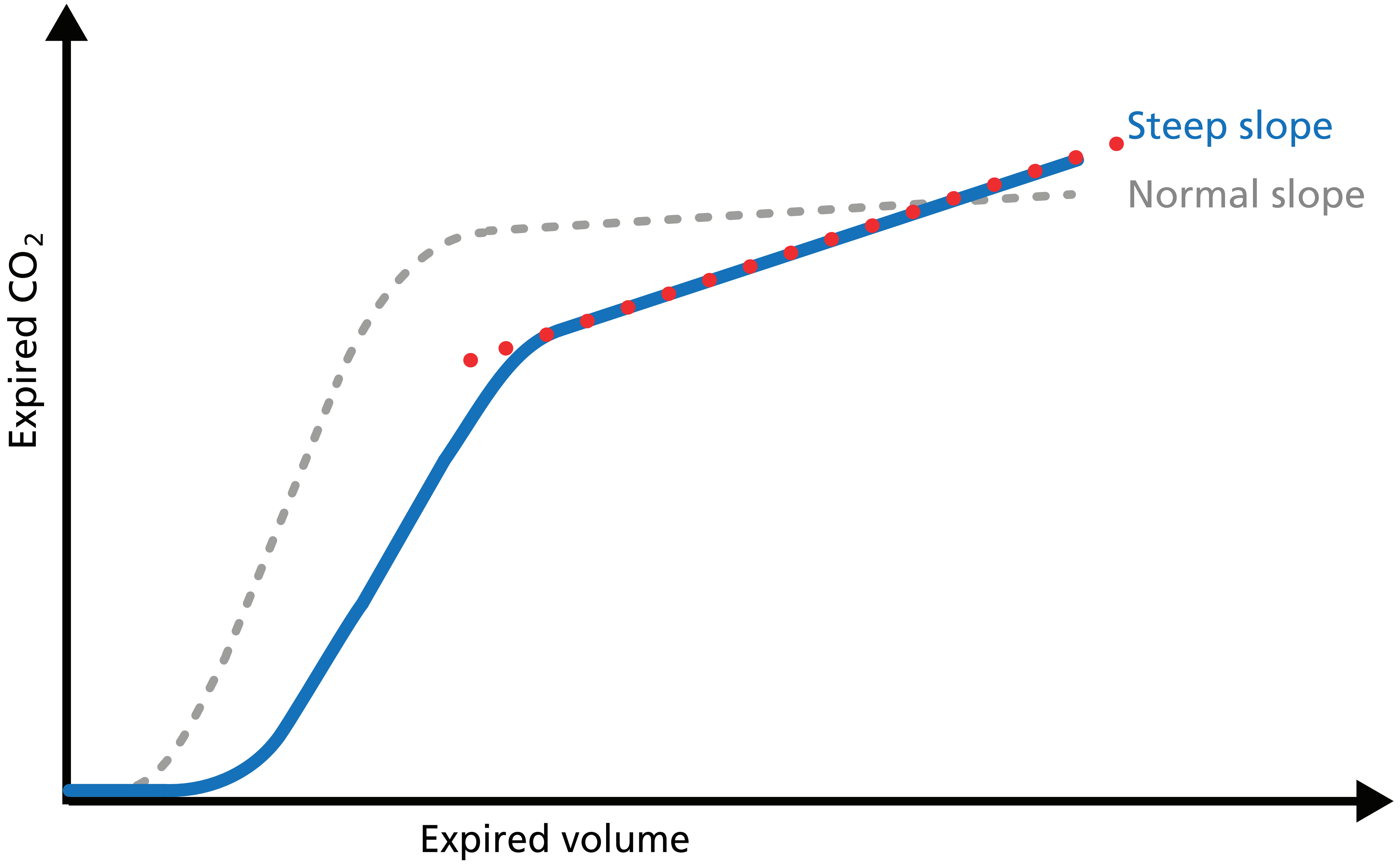




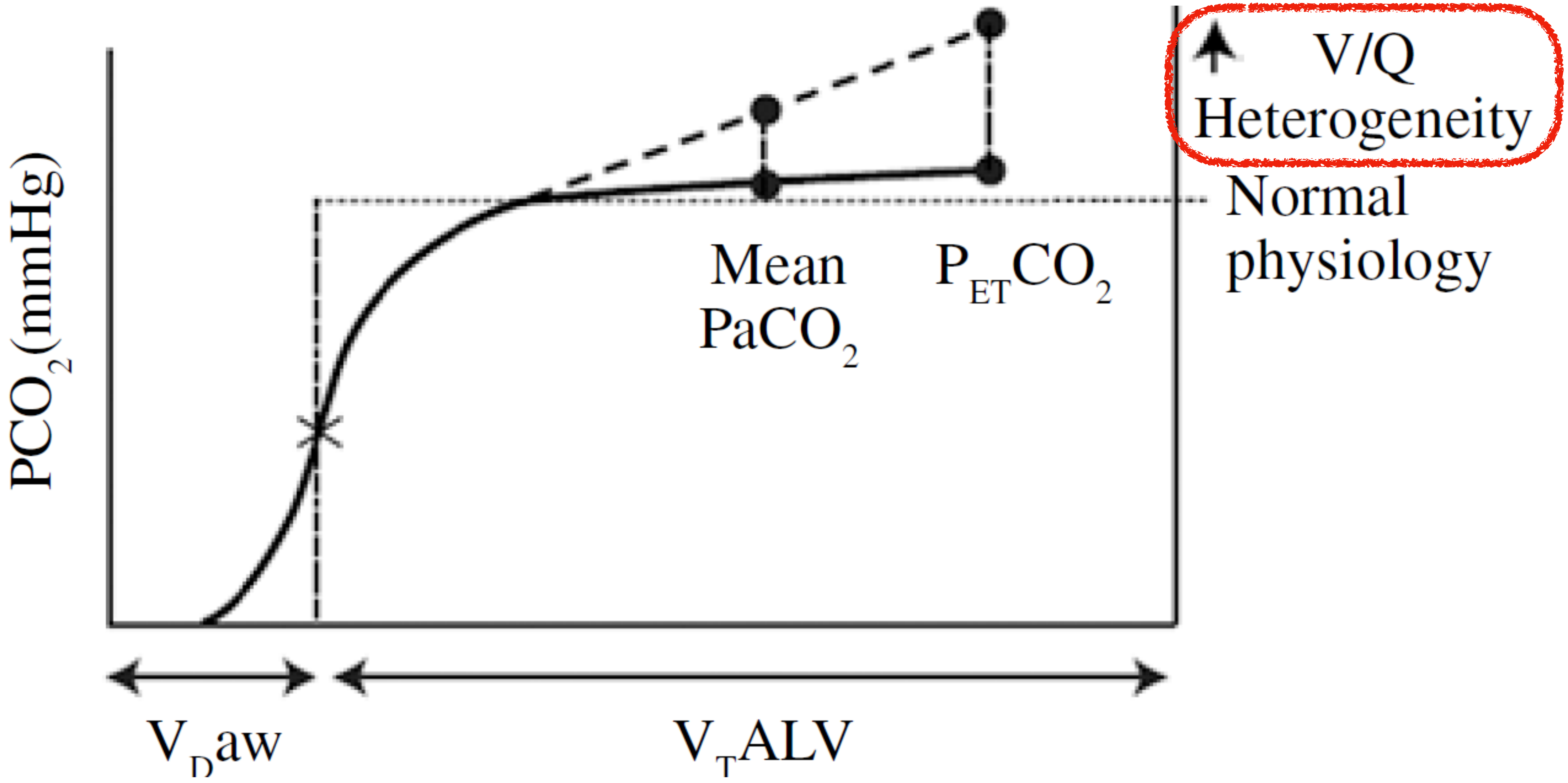
Phase IIIの傾き：slopeCO2（%CO2/L）

- Phase IIIカーブの中間の接線の傾き
- 増大：COPD、ARDSなど

A steep slope can be seen, for example, in COPD and ARDS patients.



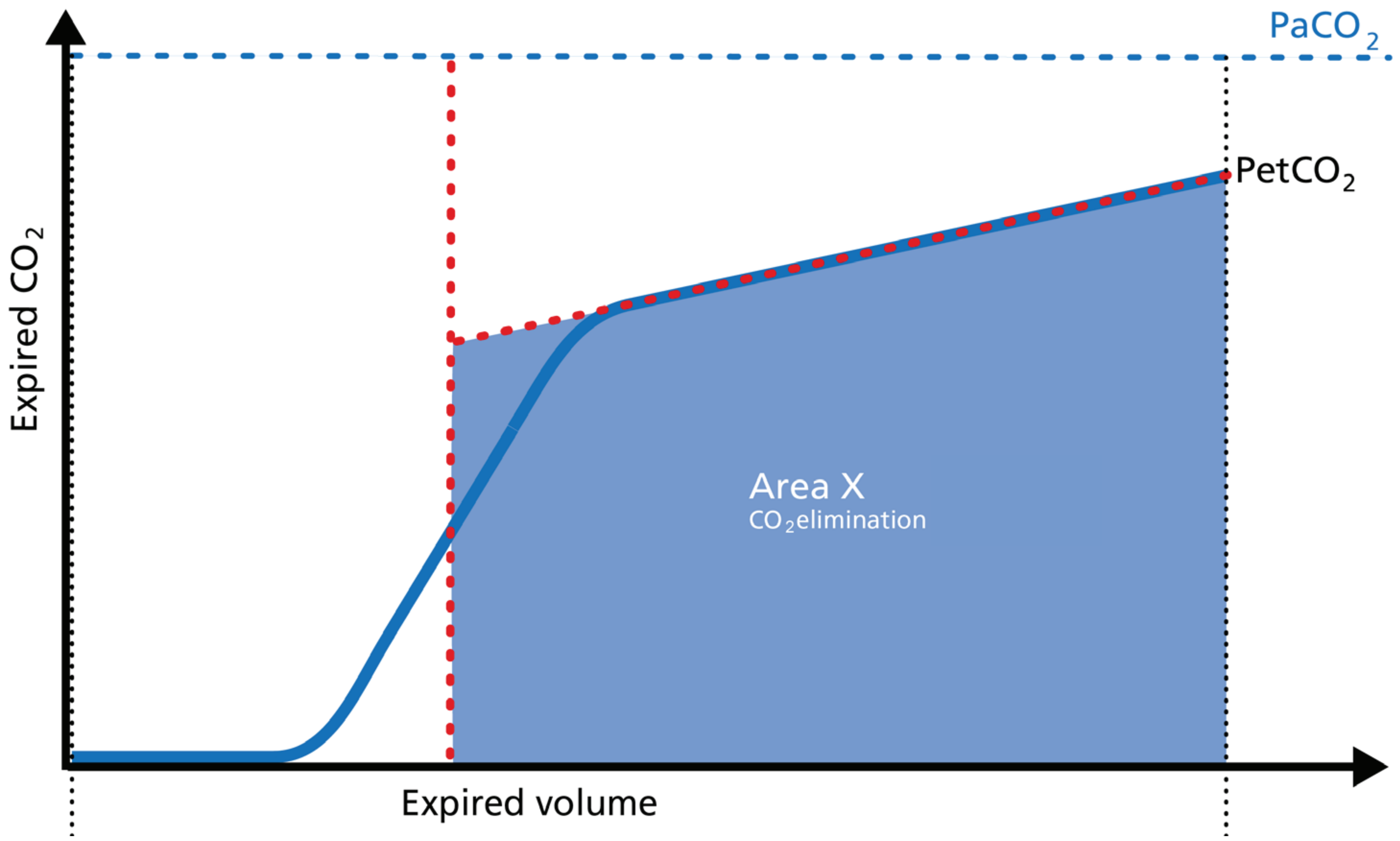
Phase IIIの傾き



CO2呼出量：V’CO2

- 1回の呼気で排出されるCO2量：VeCO2 (ml)
- 1分間の呼気で排出されるCO2量：V’CO2 (ml)
- 代謝、循環、拡散、換気、全てが影響する

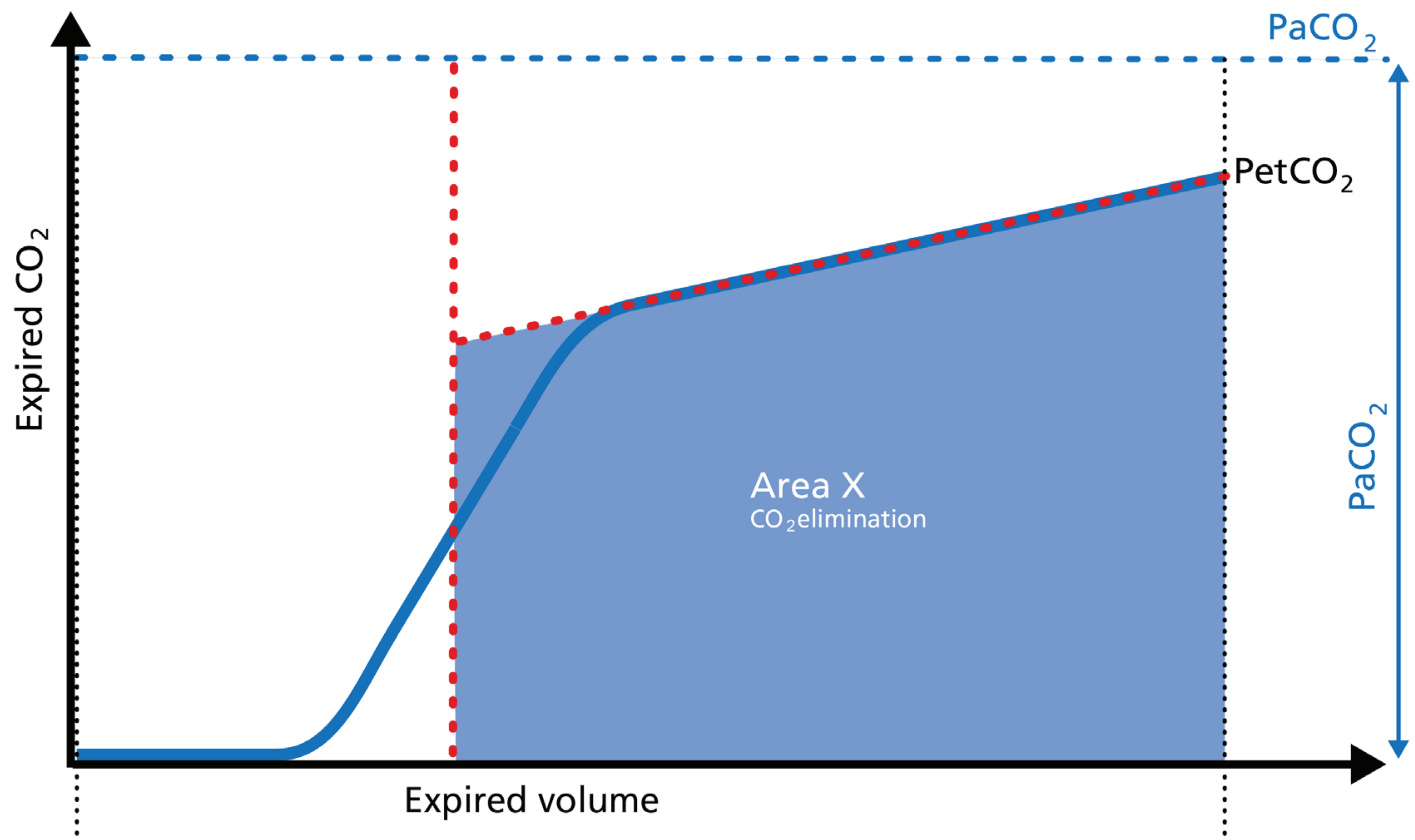
Decreasing V‘CO_2
Hypothermia, deep sedation, hypothyroidism, paralysis, and brain death decrease CO_2 production and induce a decrease in V‘CO_2.
Decreasing V‘CO_2 can also be due to a decrease in cardiac output or blood loss, and may also suggest a change in blood flow to the lung areas. Pulmonary embolism, for example, exhibits V‘CO_2 reduction and a slope reduction in Phase II.



CO2呼出量：V’CO2

Increase in V‘CO_2
is usually due to bicarbonate infusion or an increase in CO_2 production that can be caused by:

- Fever
- Sepsis
- Seizures
- Hyperthyroidism
- Insulin therapy

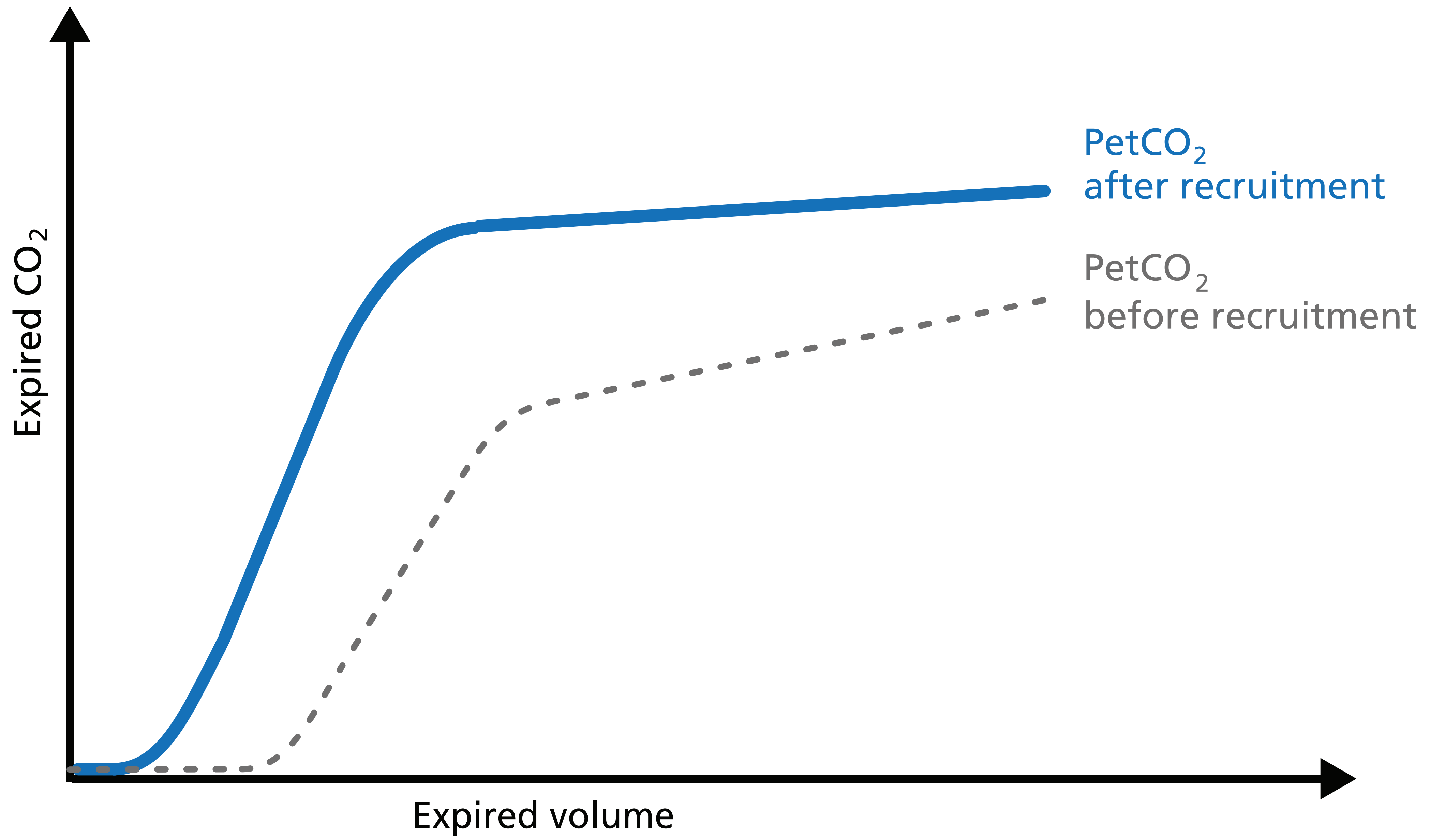


肺胞換気量：V’alv

- V’alv =RR* Vtalv = RR* (Vte-VDaw)

Increase
An increase in V‘alv is seen after an efficient recruitment maneuver and induces a transient increase in V‘CO_2.

Decrease
A decrease in V‘alv can indicate that fewer alveoli are participating in the gas exchange, for example, due to pulmonary edema.

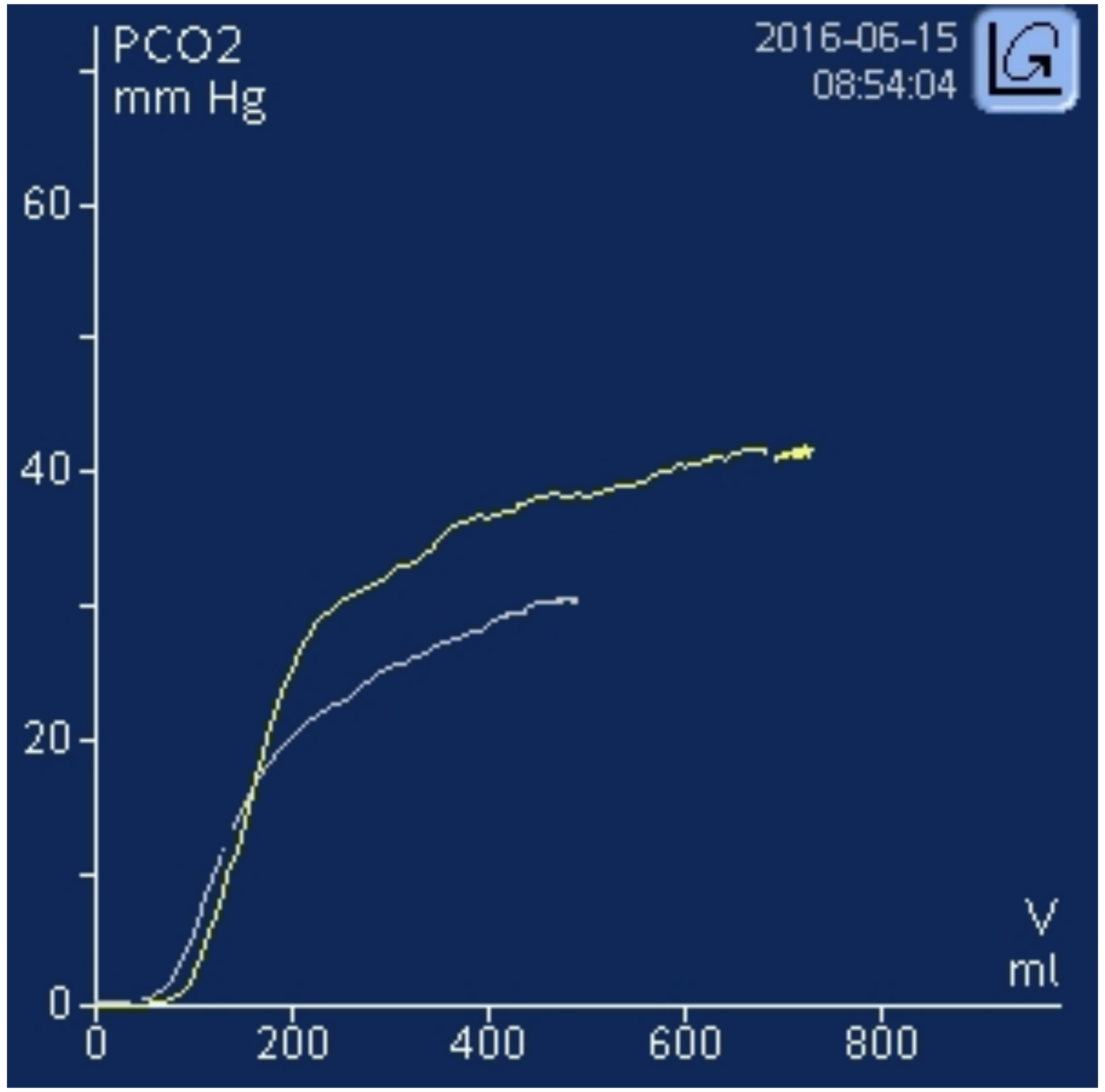


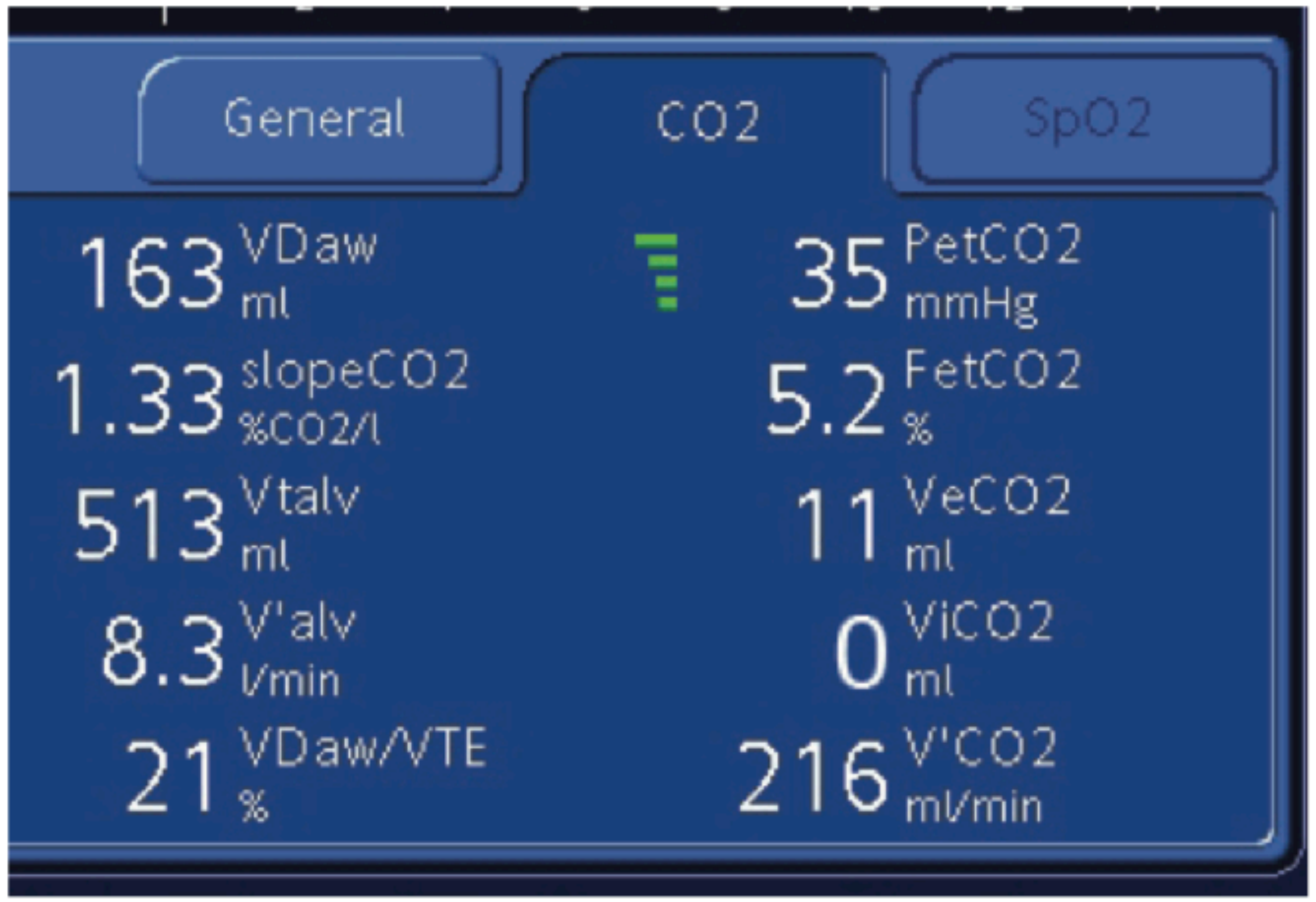
$$PaCO_2 = 0.863 \times (\dot{V}CO_2 / \dot{V}_A)$$

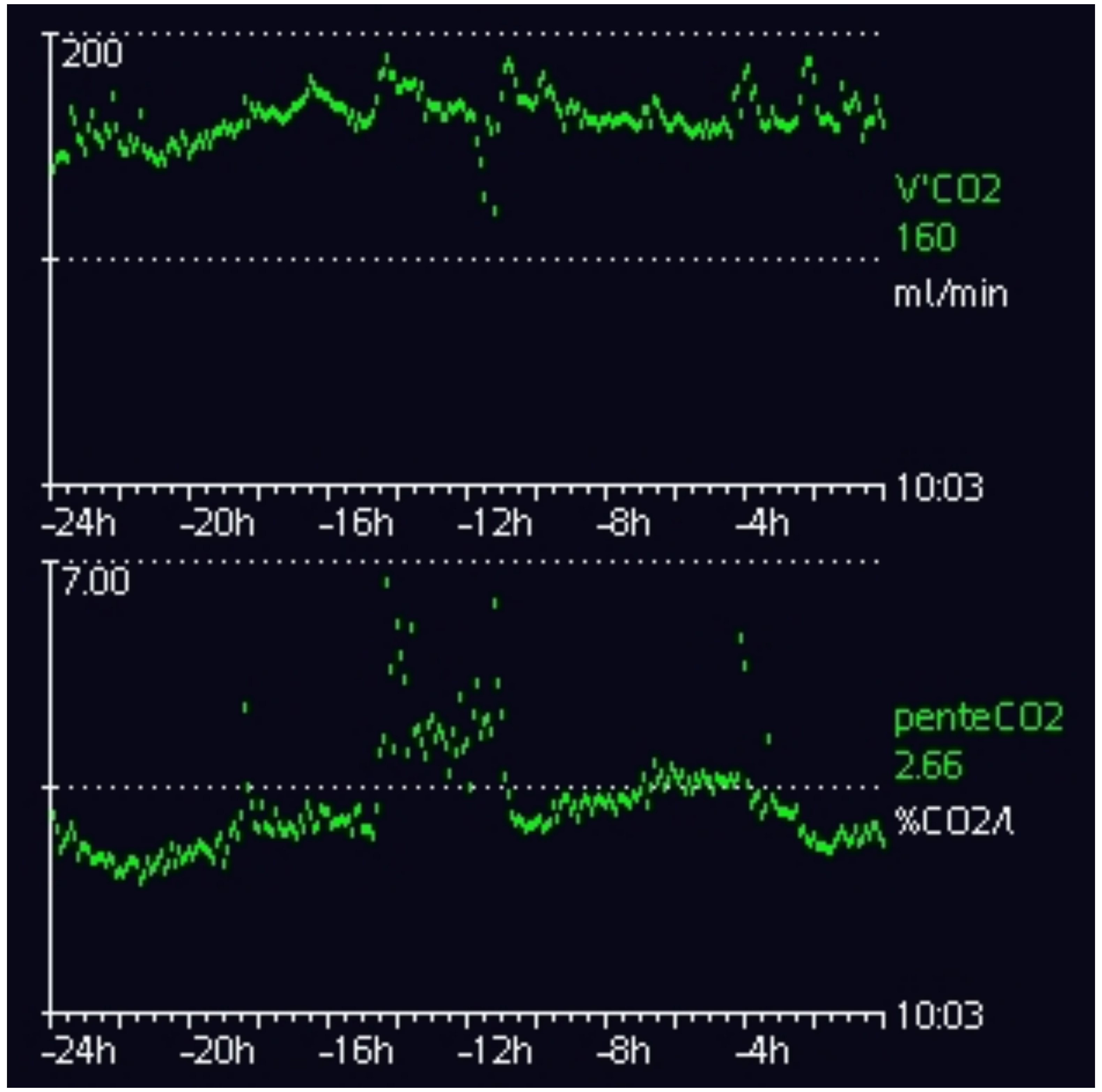
真にPaCO2と反比例するのは肺胞換気量（L/分）

ベッドサイドで分時換気量を観察しよう

ハミルトンG5におけるVolumetric Capnography







計算式

Alveolar tidal ventilation (Vtalv)：肺胞換気量

$Vtalv=Vt-VDaw$

Alveolar minute ventilation (V' alv)：分時肺胞換気量

$V'alv=f*Vtalv$

Volume of CO_2 eliminated in one breath (VCO_2)：二酸化炭素排泄量

$VCO_2=VeCO_2-ViCO_2$

Fractional concentration of CO_2 in exhaled gas ($FeCO_2$)：二酸化炭素濃度

$FeCO_2=V'CO_2/MinVol$

Partial pressure of CO_2 in exhaled gas ($PeCO_2$)：二酸化炭素分圧

$PeCO_2=FeCO_2*(Pb-PH_2O)$

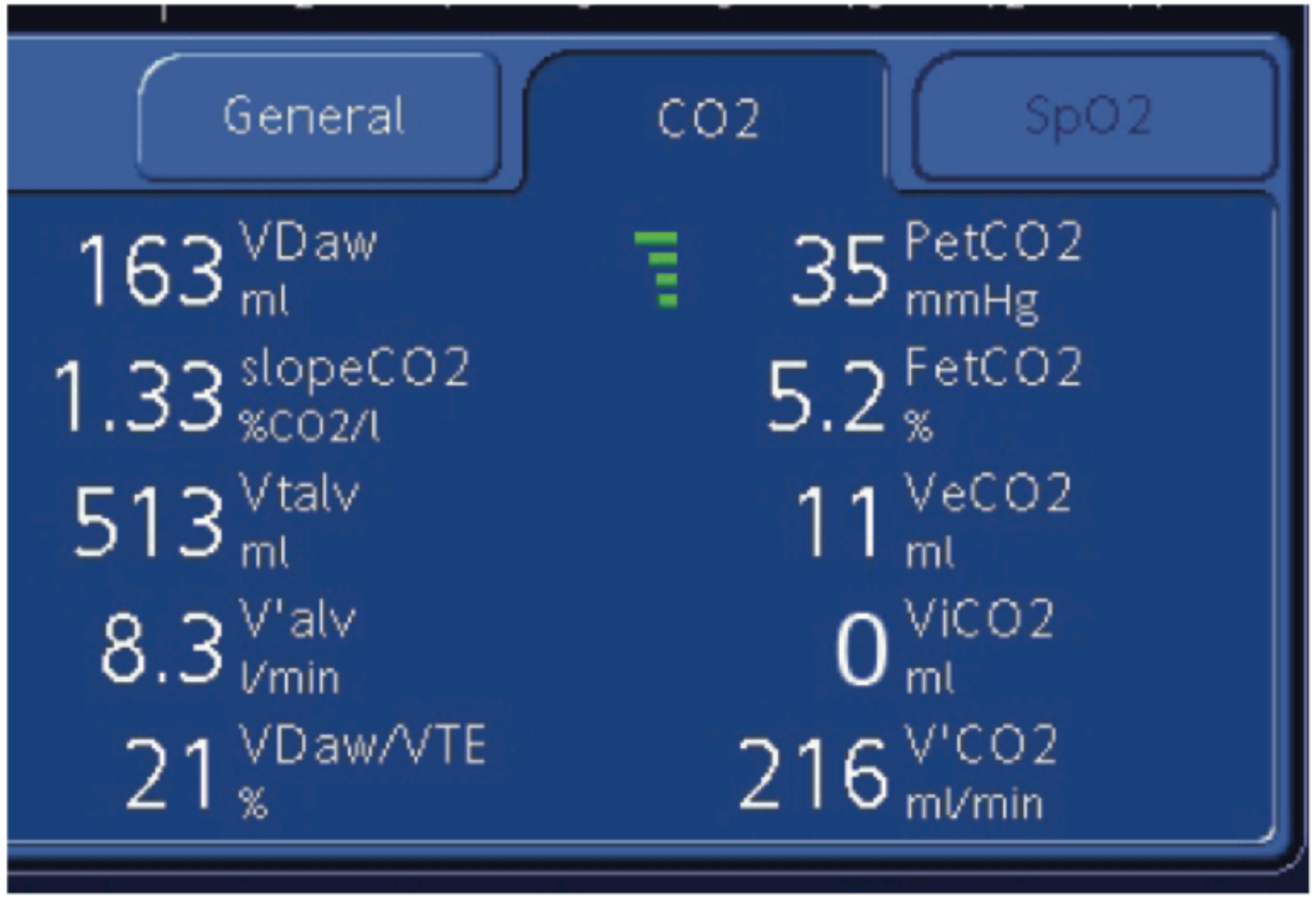
Bohr dead space fraction (VDbohr/Vt) (Note: Vt in this formula needs to be in ml STPD)

$VDbohr/Vt=1-(VeCO_2/(Vt*FeCO_2))$

Physiological dead space fraction (VD/Vt)：エアウェイ死腔濃度

$VD/Vt=1-((VeCO_2/Vt)/(paCO_2/Pb-PH_2O))$

パラメーターと参考値



Description	Unit[2]	Normal
VD_{aw}	ml	2.2 ml/kg IBW
$slopeCO_2$	$\%CO_2/l$	31324 * Vt-1.535
$V'CO_2$	ml/min	2.6 to 2.9 ml/min/kg
$FetCO_2$	%	5.1% to 6.1%
V'alv	l/min	0.052 to 0.070 l/min/kg

臨床応用

代謝の影響

上昇

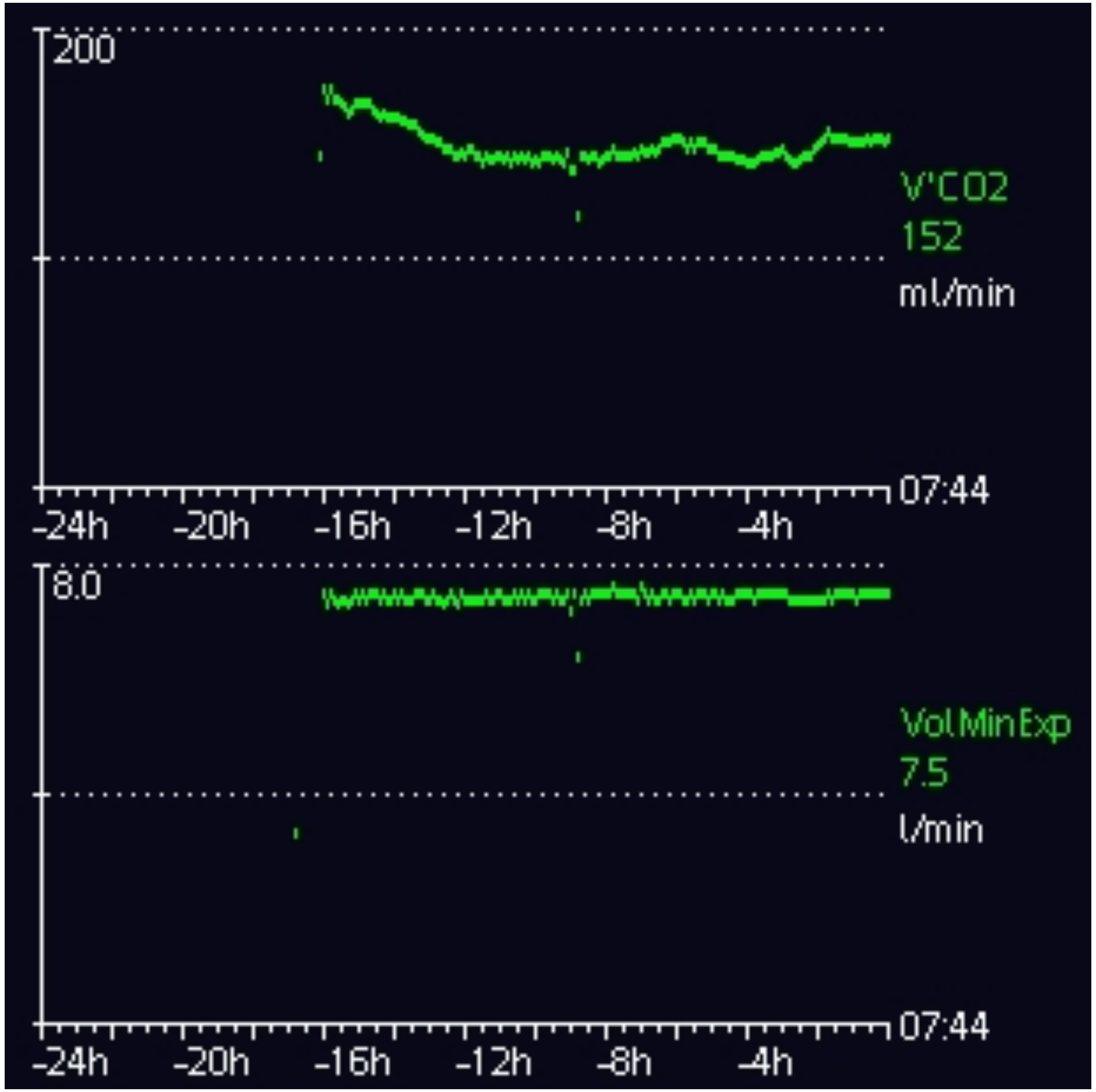
- 発熱
- 敗血症
- シバリング
- 痙攣
- 重炭酸投与
- 甲状腺機能亢進
- インスリン療法

低下

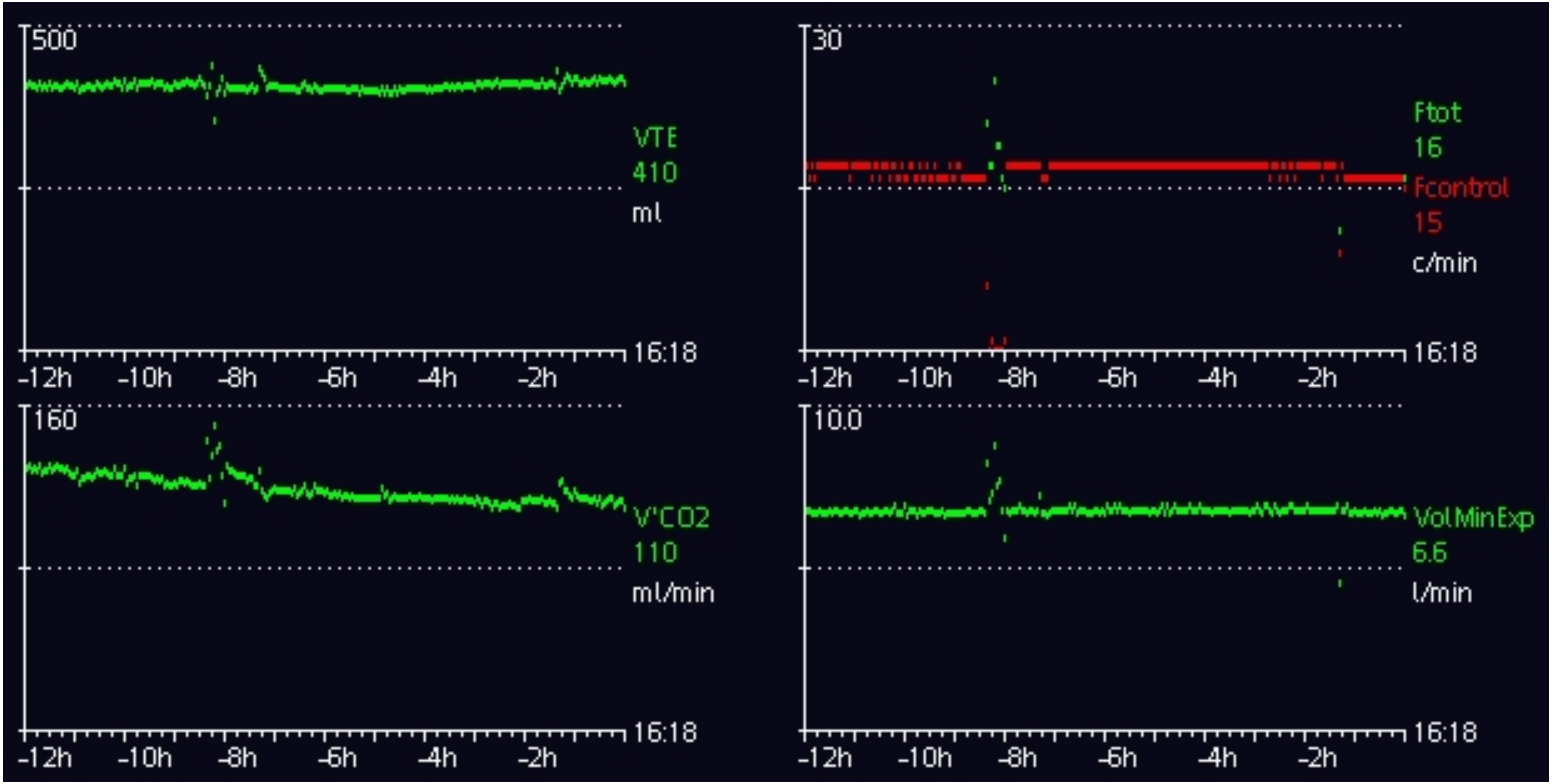
- 低体温
- 鎮静
- 筋弛緩

低体温

- V’CO2の低下
- 分時換気量変化なし

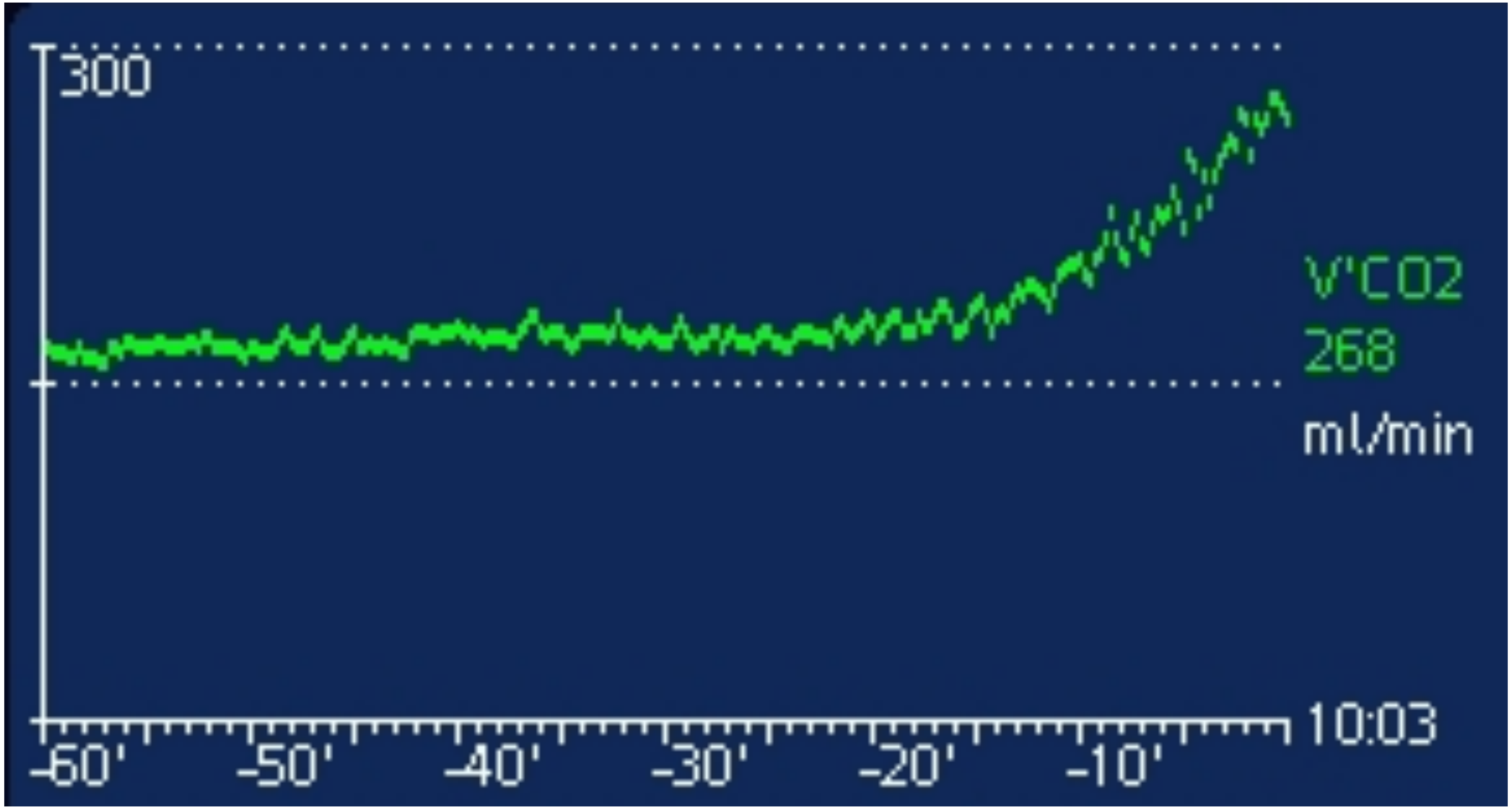


鎮静

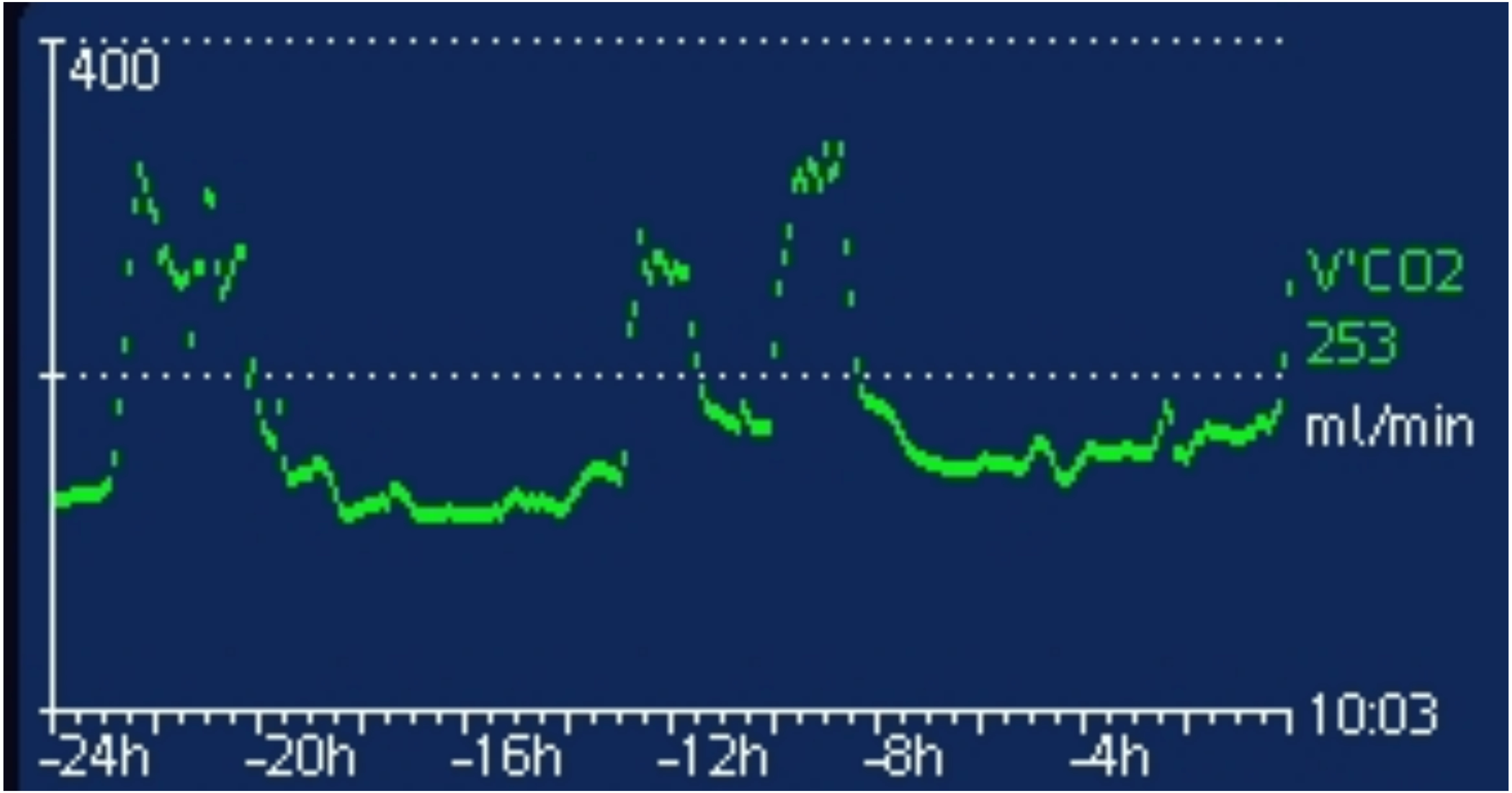


500
VTE
410
ml
16:18
-12h
-10h
-8h
-6h
-4h
-2h
30
Ftot
16
Fcontrol
15
c/min
160
V'CO2
110
ml/min
10.0
VolMinExp
6.6
l/min

敗血症



痙攣発作



脳死

循環の影響

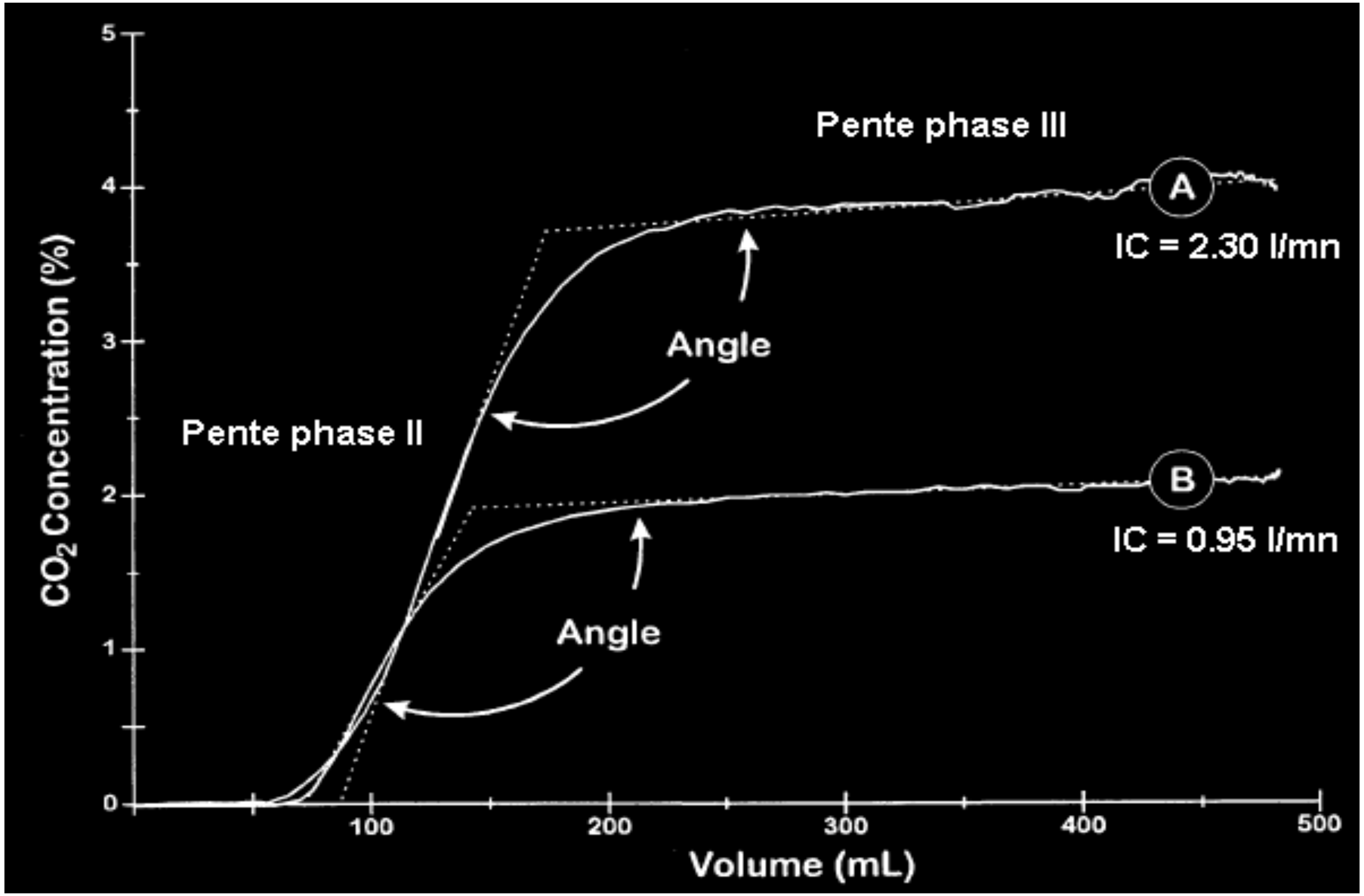
VCO2増大

- 抹消拡張
- 心拍出量増加
  - ✓ 輸液蘇生
  - ✓ ドブタミン
  - ✓ エピネフリン

VCO2減少

- 心拍出量低下
- ショック
- 肺塞栓

出血性ショック



角度は変わらない = 抵抗・肺の状態は変わらない

…n. Intensive Care Med 2000

肺塞栓

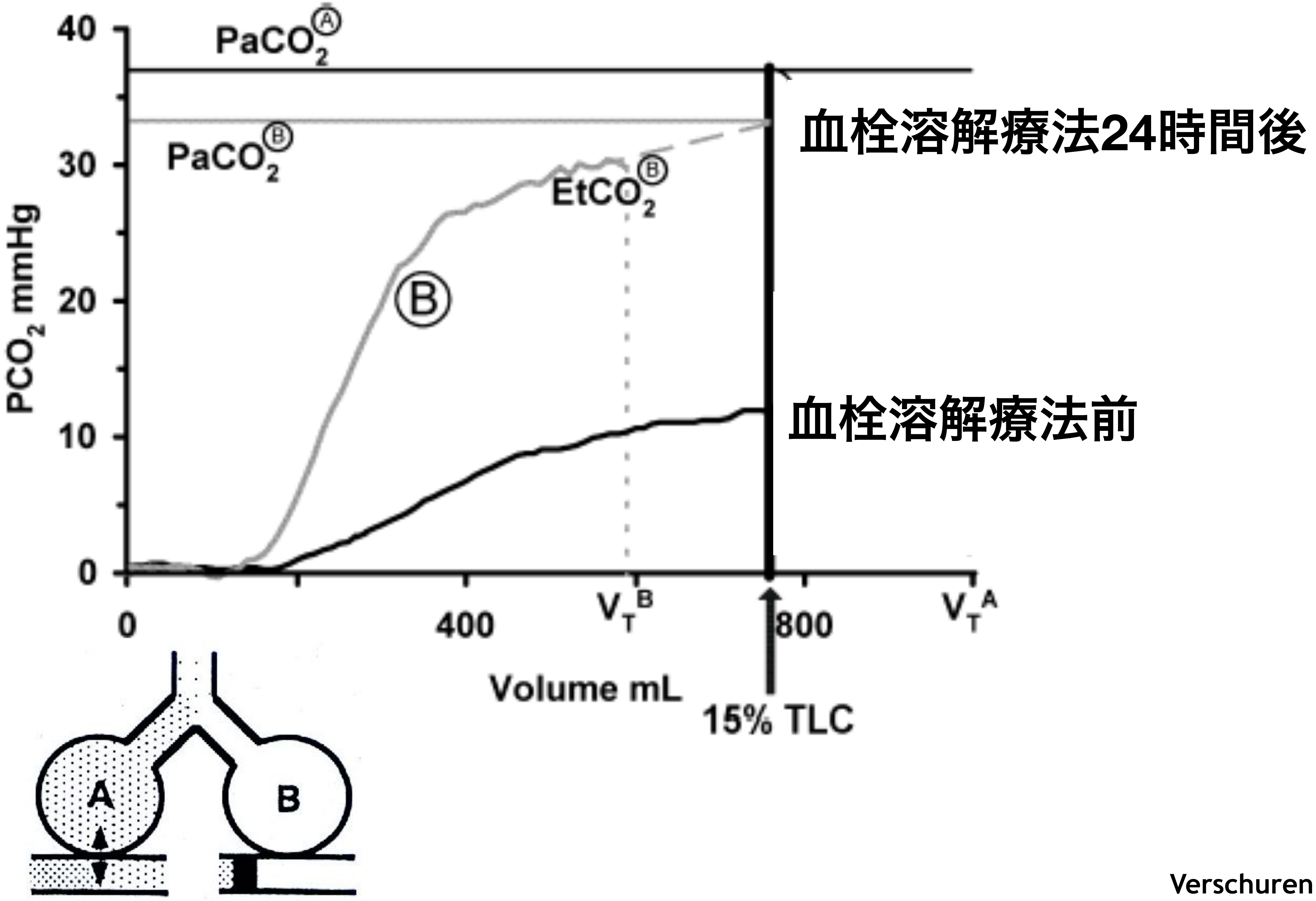
血行動態安定

- Va/Q 不均衡
- 肺胞死腔増大
- phase IIIの傾き増加
- VCO2の急激な低下

ショック

- Va/Q 不均衡 + ショック
- VCO2の急激な低下

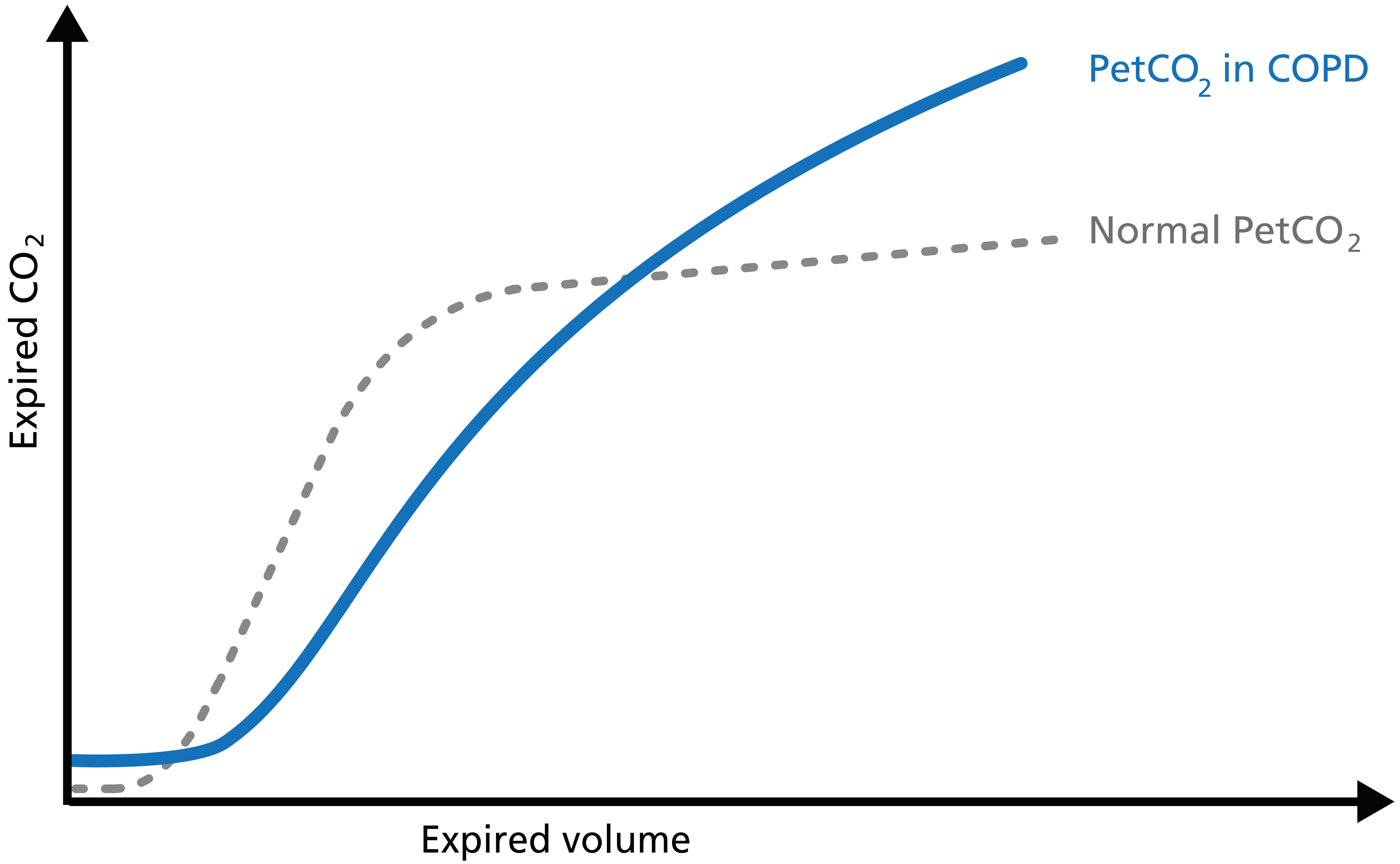
肺塞栓



Verschuren. Intensive Care Med 2004

閉塞性肺疾患

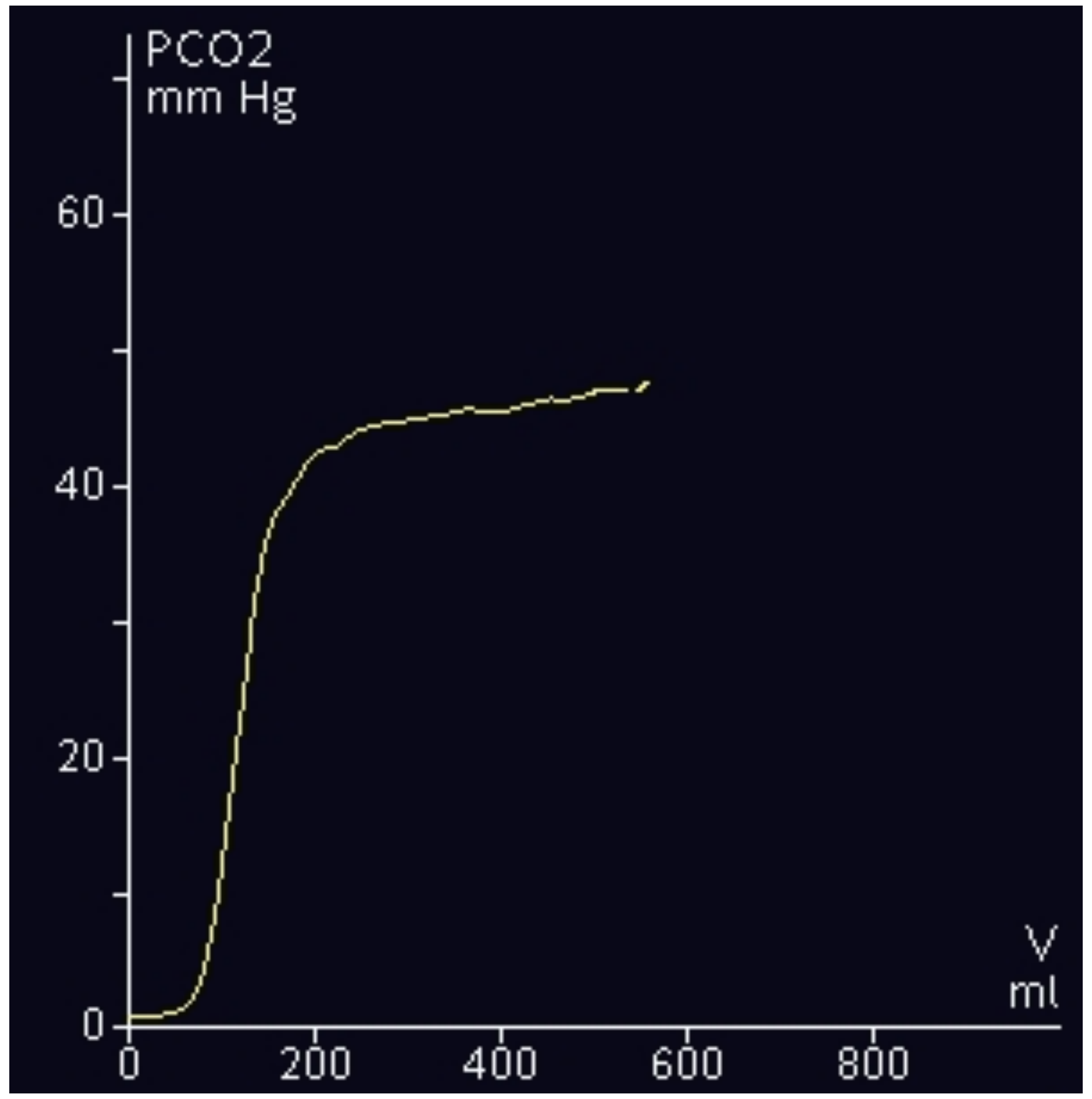
The volumetric capnogram in COPD patients shows a prolonged Phase II, an increase in $PetCO_2$, and a continuously ascending slope without plateau in Phase III.



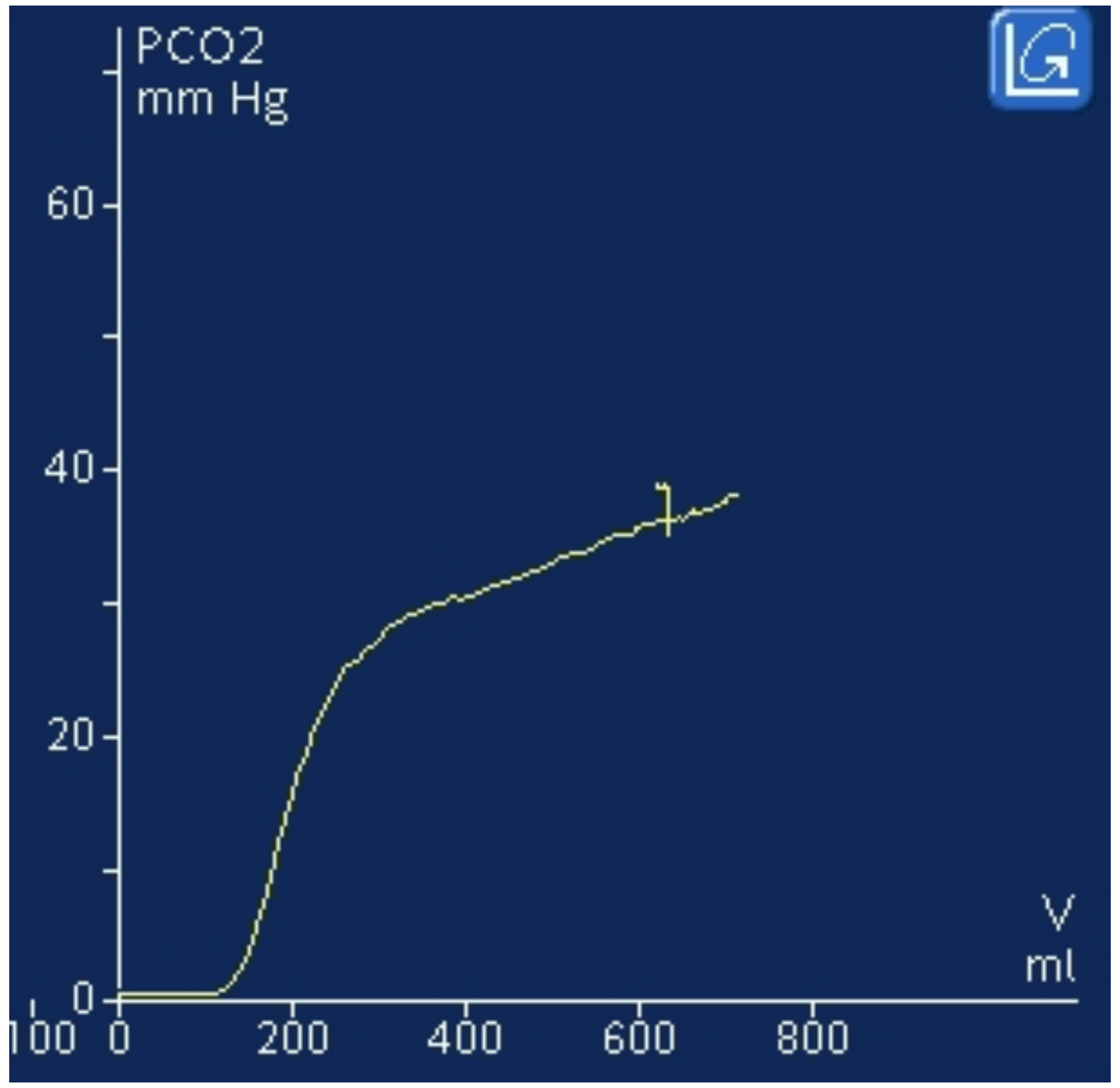
Phase II延長、Phase IIIの傾き↑、PetCO2↑

閉塞性肺疾患

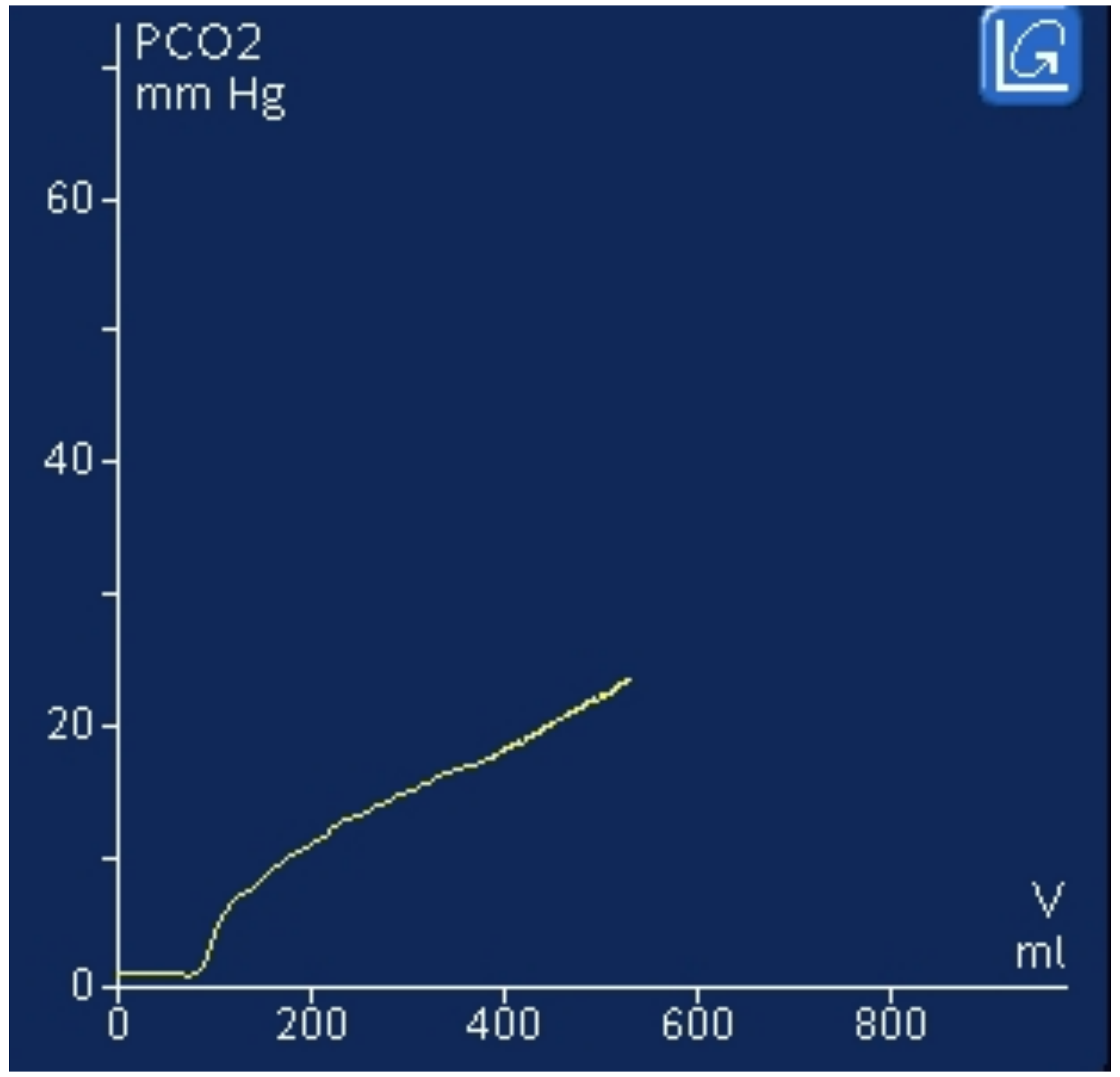
正常



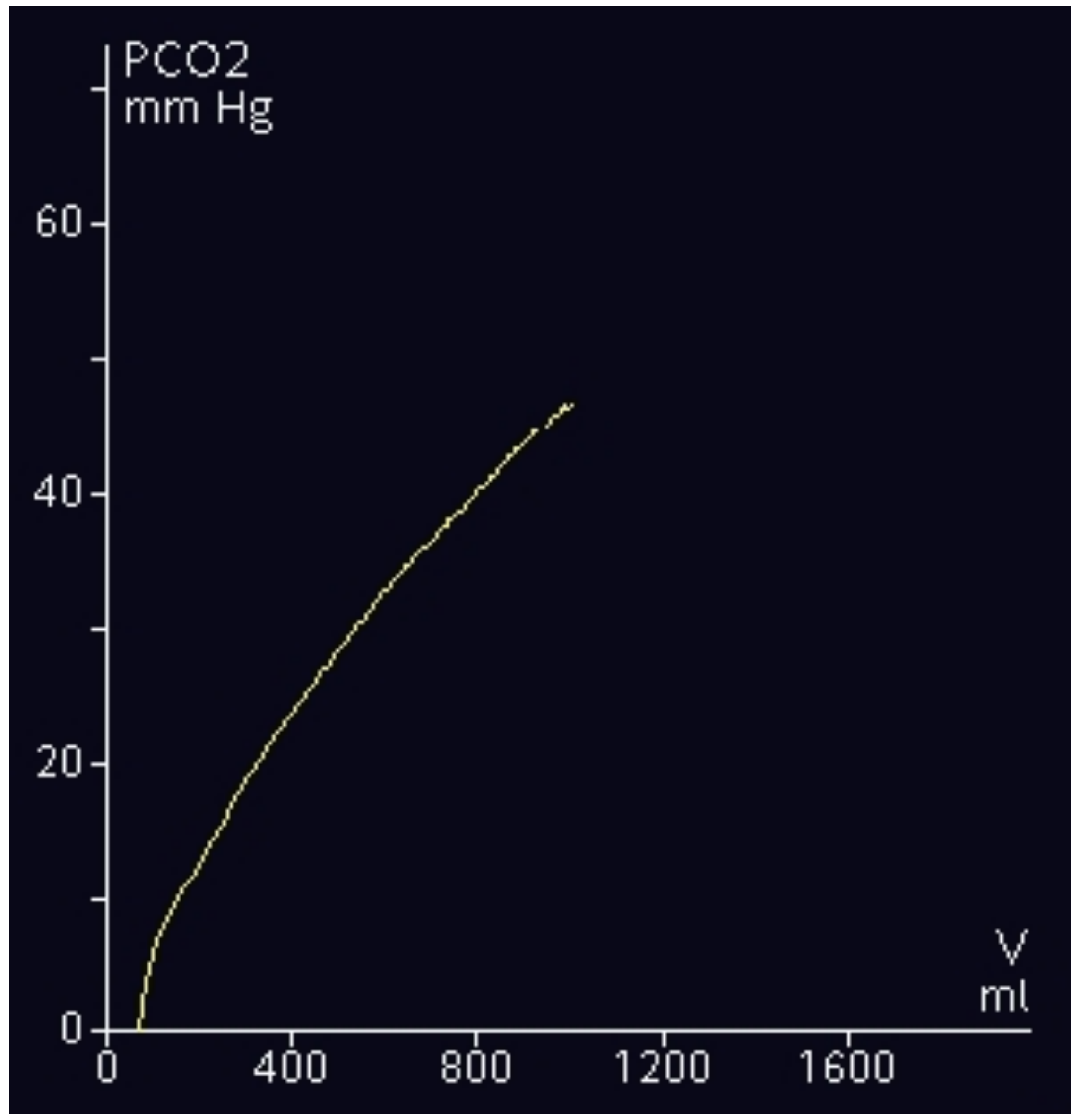
軽症 COPD



中等症 COPD



重症 COPD

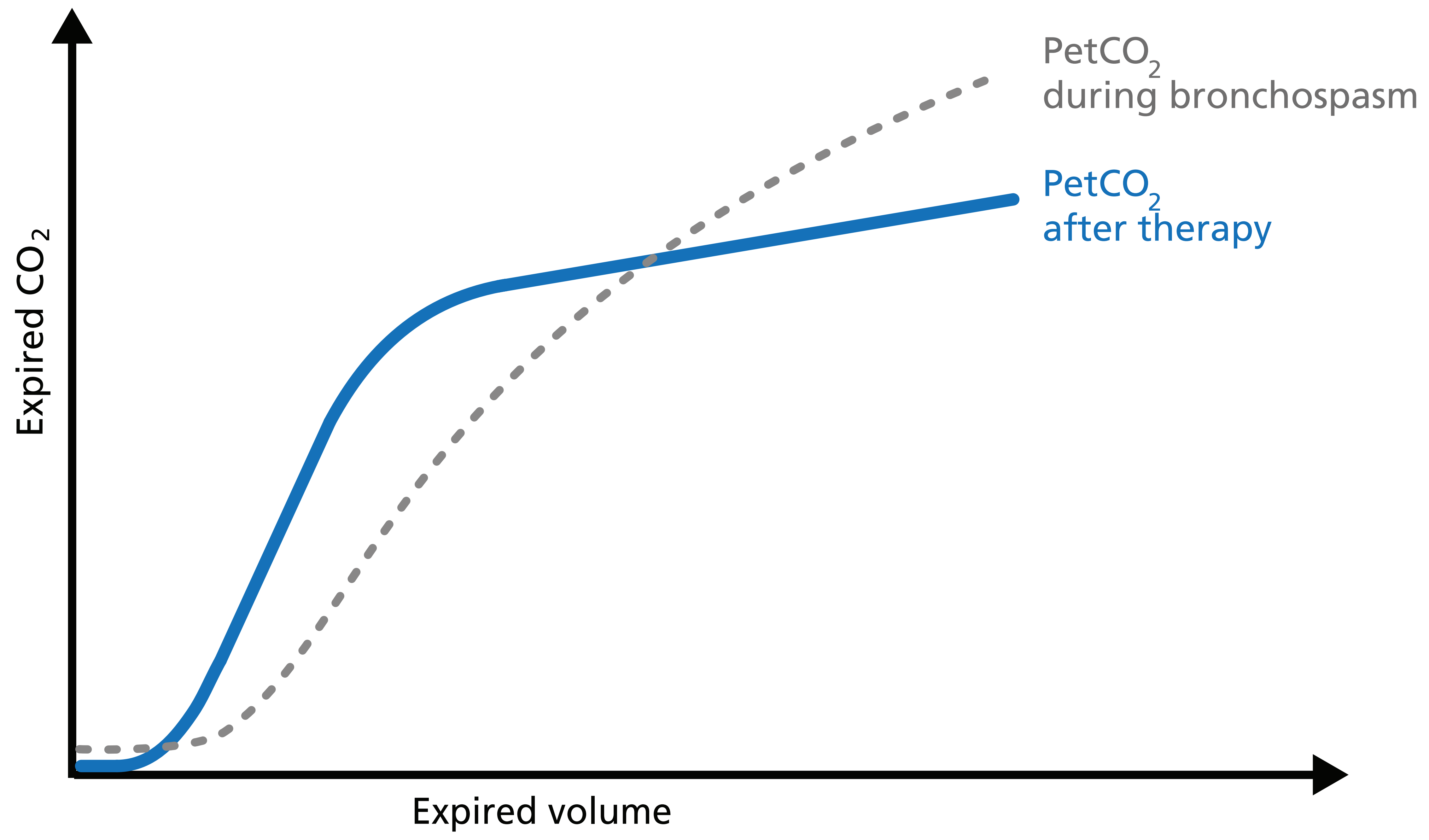


重症度による波形の違い

気管支攣縮：気管支拡張薬投与

A Phase II shift to the left indicates reduced resistance.

Phase III slope shows a decrease in steepness indicating better gas distribution and reduced alveolar dead space (VD_{alv}).



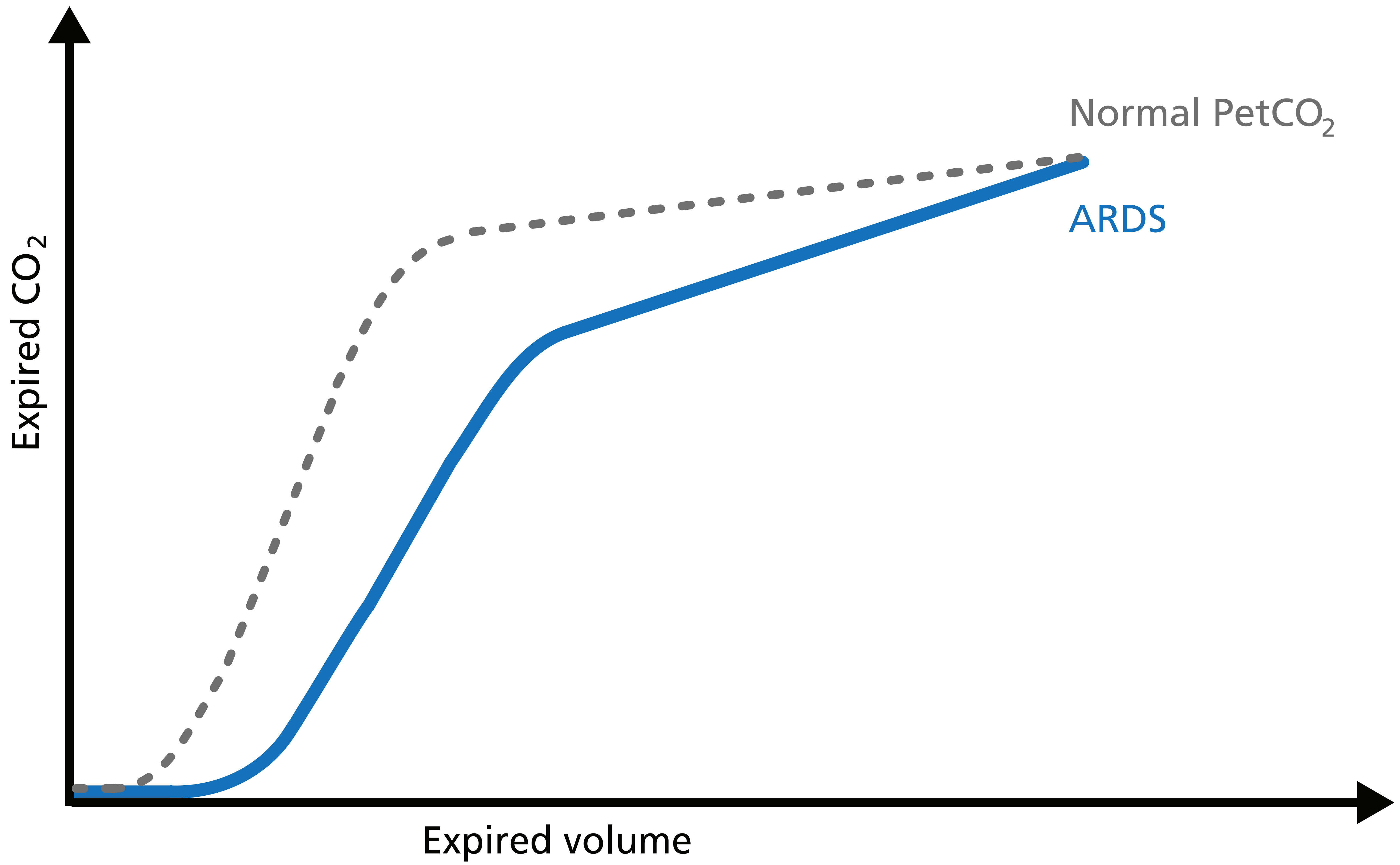
呼気抵抗↓、Phase IIIの傾き↓

ARDS

Phase I is larger due to increased anatomical dead space caused by PEEP.

The slope of Phase II is decreased due to lung perfusion abnormalities.

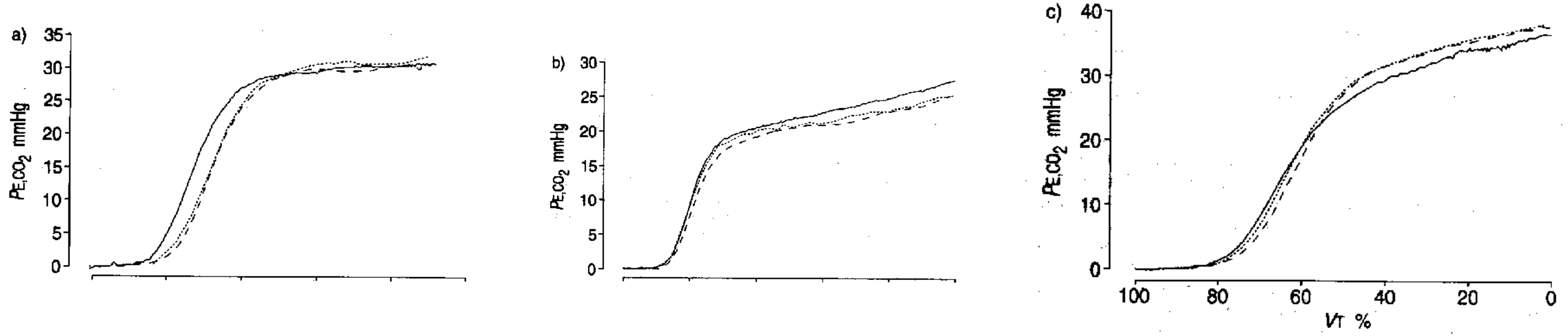
The slope of Phase III is increased due to lung heterogeneity.



Phase I ↑、Phase IIの傾き↓、Phase IIIの傾き↑

ARDS

CONTROL ALI ARDS



重症度による波形の違い

Blanch.Eur Respir J 1999.

PULMONARY DEAD-SPACE FRACTION AS A RISK FACTOR FOR DEATH IN THE ACUTE RESPIRATORY DISTRESS SYNDROME

THOMAS J. NUCKTON, M.D., JAMES A. ALONSO, R.R.T., RICHARD H. KALLET, R.R.T., M.S., BRIAN M. DANIEL, R.R.T., JEAN-FRANÇOIS PITTET, M.D., MARK D. EISNER, M.D., M.P.H., AND MICHAEL A. MATTHAY, M.D.

N Engl J Med, Vol. 346, No. 17 · April 25, 2002

TABLE 3. ODDS RATIOS FOR VARIABLES INDEPENDENTLY ASSOCIATED WITH AN INCREASED RISK OF DEATH.*

VARIABLE	ODDS RATIO (95% CI)	P VALUE
Dead-space fraction (per increase of 0.05)†	1.45 (1.15–1.83)	0.002
SAPS II (per 1-point increase)	1.06 (1.03–1.08)	<0.001
Quasistatic respiratory compliance (per decrease of 1 ml/cm of water)	1.06 (1.01–1.10)	0.01

死腔換気率は死亡予測リスク因子

PULMONARY DEAD-SPACE FRACTION AS A RISK FACTOR FOR DEATH IN THE ACUTE RESPIRATORY DISTRESS SYNDROME

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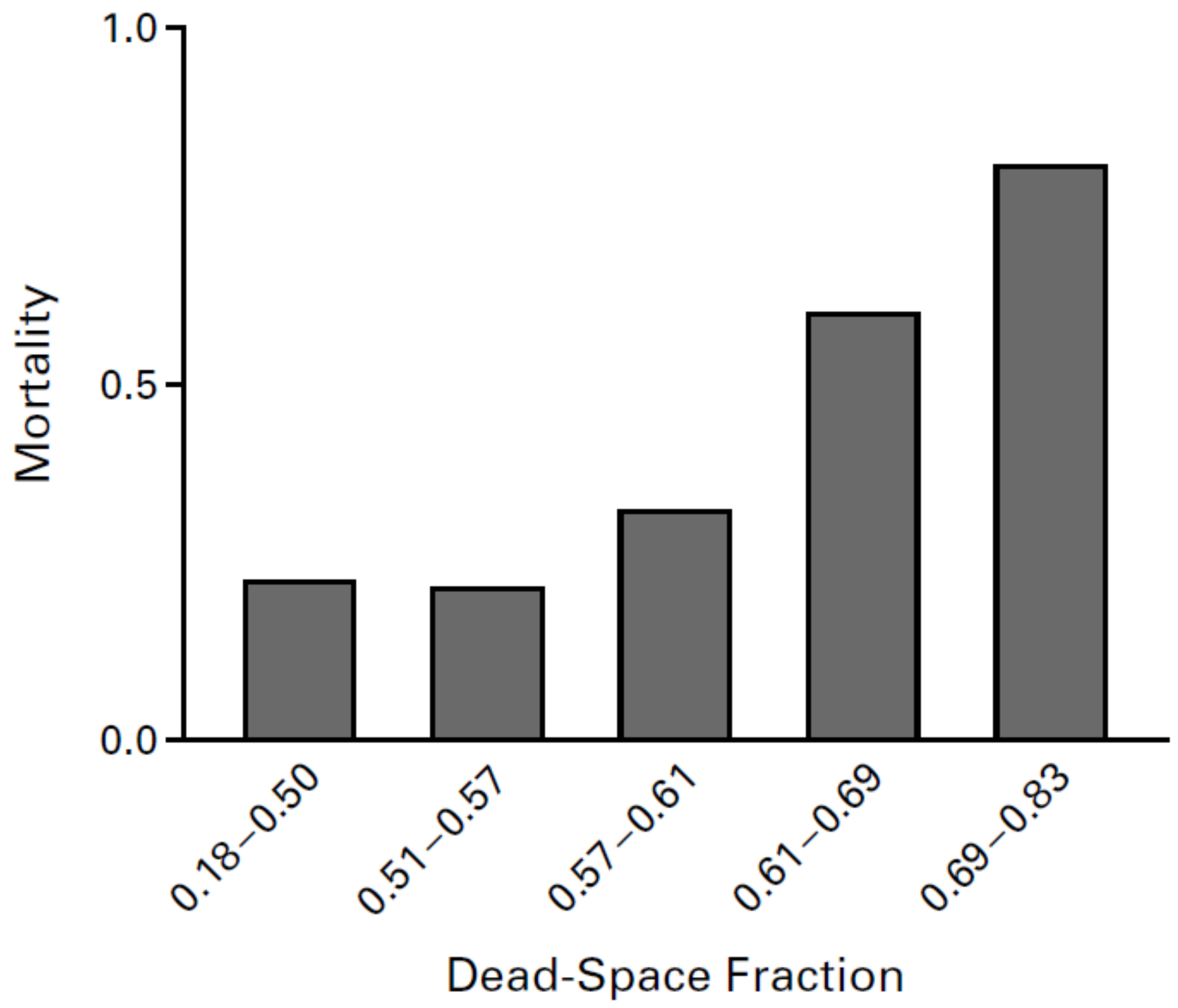

死腔換気率が大きいほど死亡率が高い

Prognostic Value of the Pulmonary Dead-Space Fraction During the Early and Intermediate Phases of Acute Respiratory Distress Syndrome

Joan M Raurich MD PhD, Margalida Vilar MD, Asunción Colomar MD, Jordi Ibáñez MD PhD, Ignacio Ayestarán MD, Jon Pérez-Bárcena MD, and Juan A Llompart-Pou MD

Early phase	Odds Ratio	95% CI	*P*
Dead-space fraction, per increase of 0.05	1.59	1.18–2.16	.003
Age, per 1-year increase	1.06	1.02–1.10	.004
SOFA, per 1-point increase	1.44	1.17–1.77	.001

Intermediate phase	Odds Ratio	95% CI	*P*
Dead-space fraction, per increase of 0.05	2.87	1.36–6.04	.005
Age, per 1-year increase	1.09	1.01–1.18	.03
SOFA, per 1-point increase	2.35	1.22–4.53	.01

死腔換気率は死亡予測リスク因子

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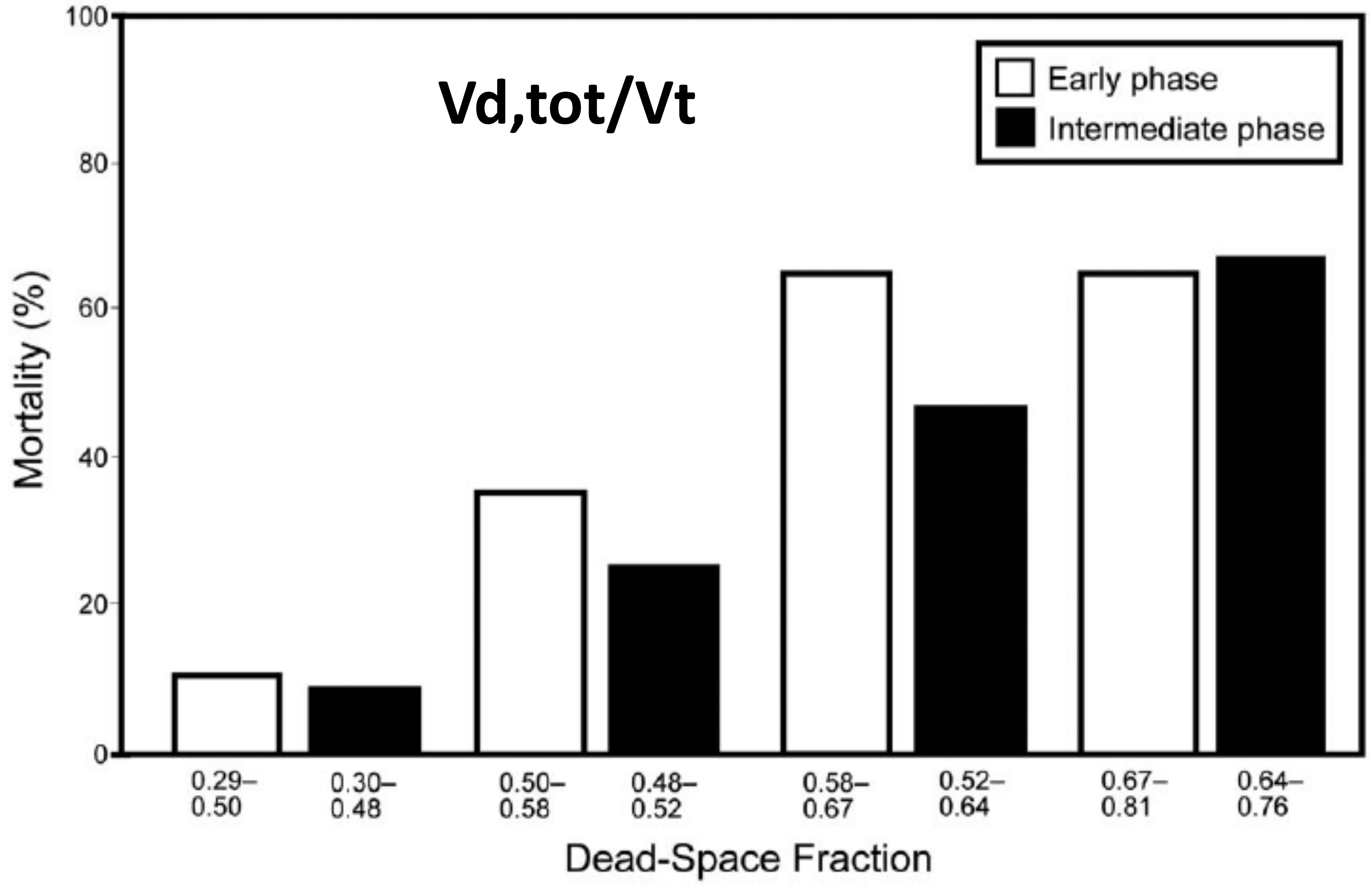

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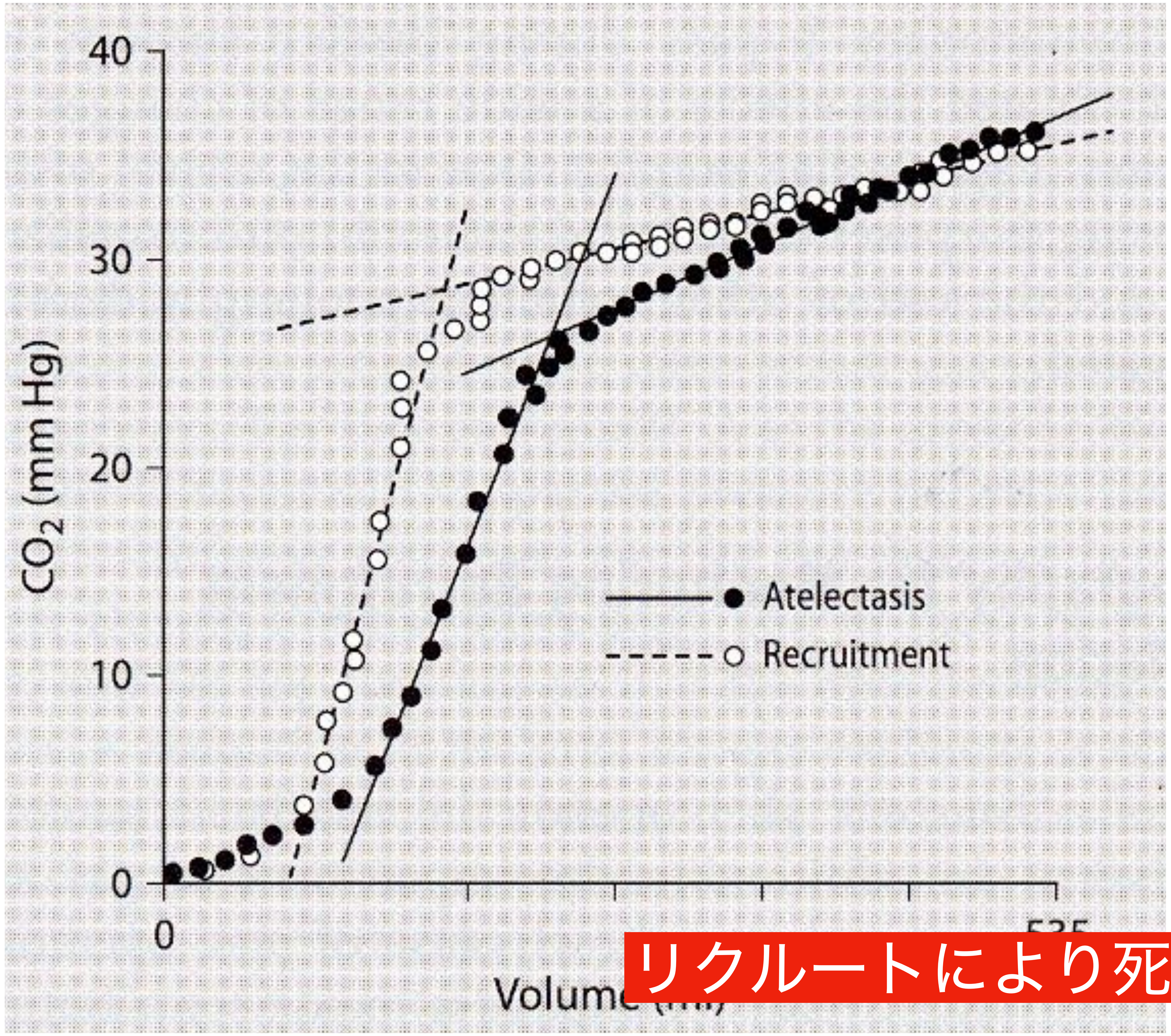
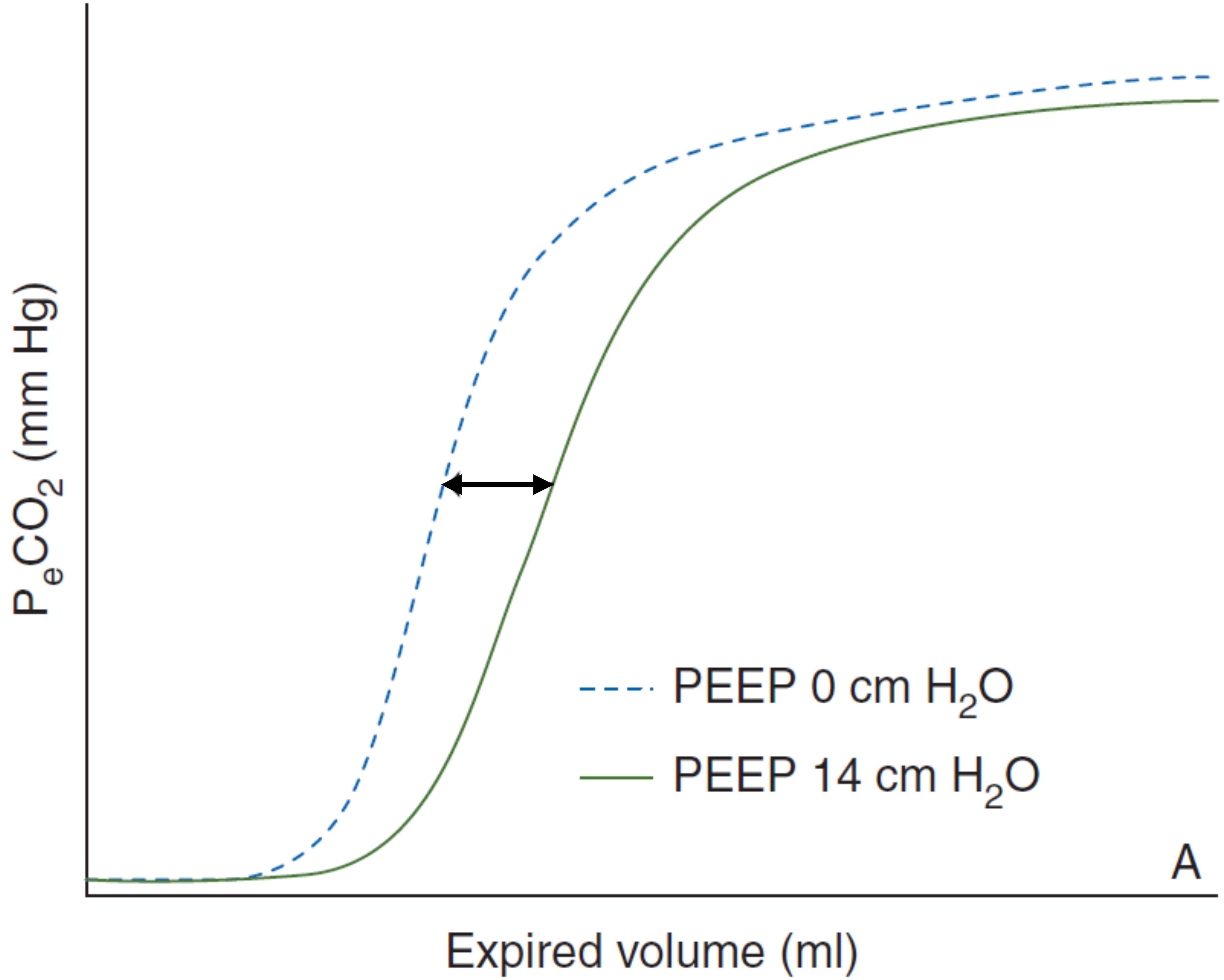
ARDS：リクルートメントの効果



リクルートにより死腔が減少

Suarez F et al. Yearbook of Intensive Care Medicine 2006

PEEP vs. 死腔



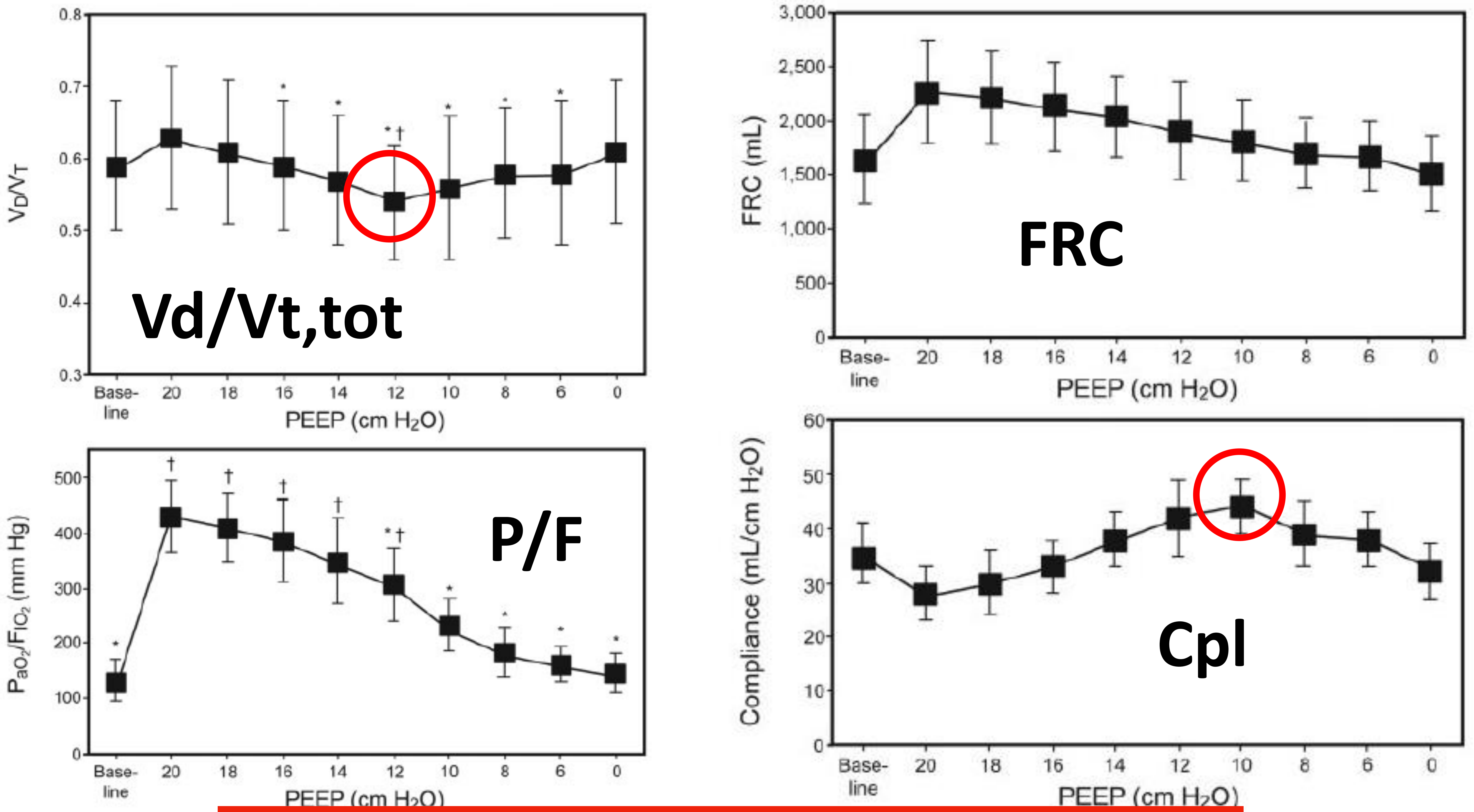
15 normal lung patients

PEEPは死腔増大効果あり：過膨張の可能性

Blankman. BJA 2016

Dead Space Fraction Changes During PEEP Titration Following Lung Recruitment in Patients With ARDS

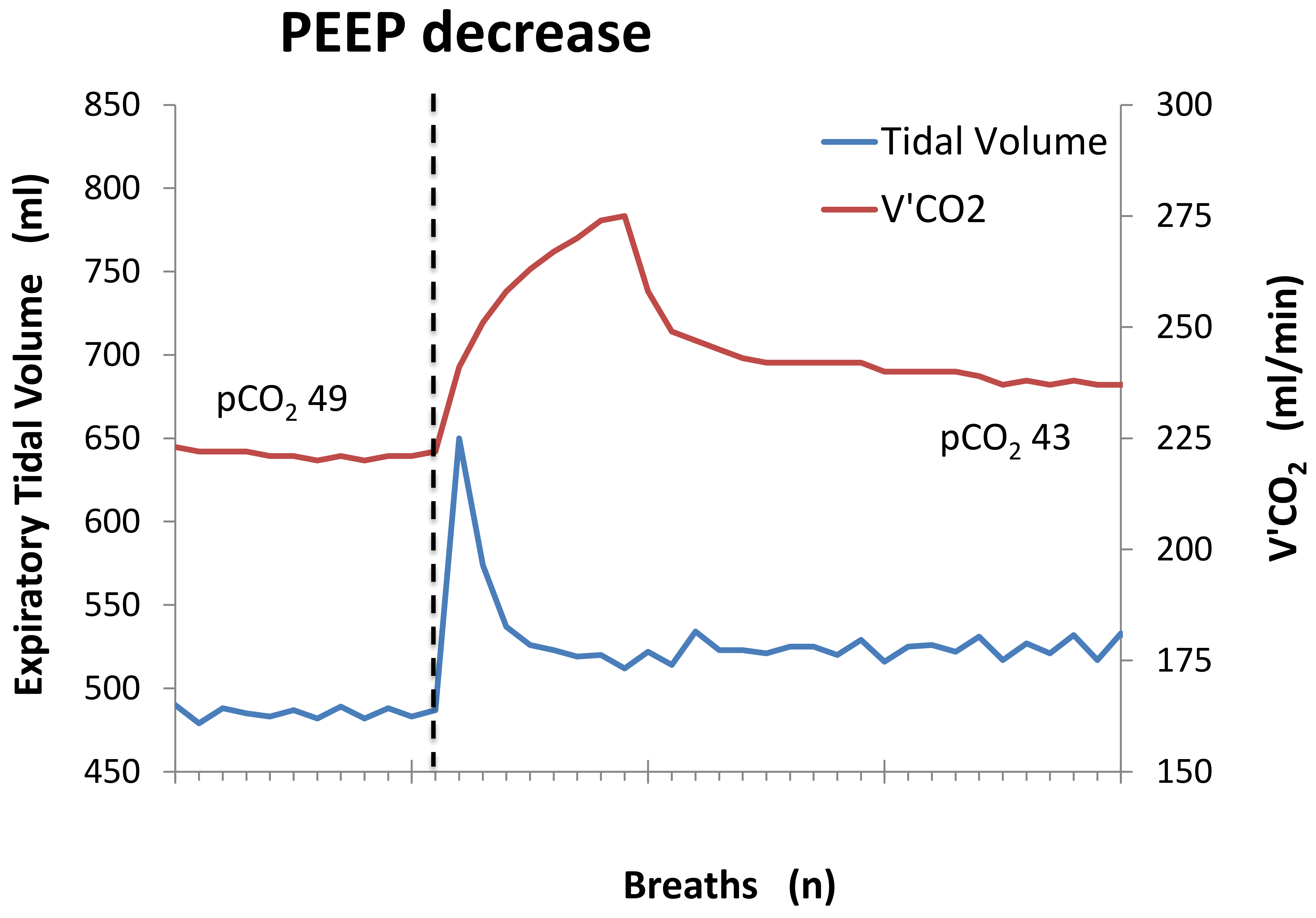
GUO Fengmei PhD, CHEN Jin MD, LIU Songqiao MD,
YANG Congshan MD, and YANG Yi MD



死腔換気率をPEEP titrationに使用可能

他の方法と異なる結果

V'CO_2 change after modifications of MV is related to CO_2 removal and may predict final arterial pCO_2

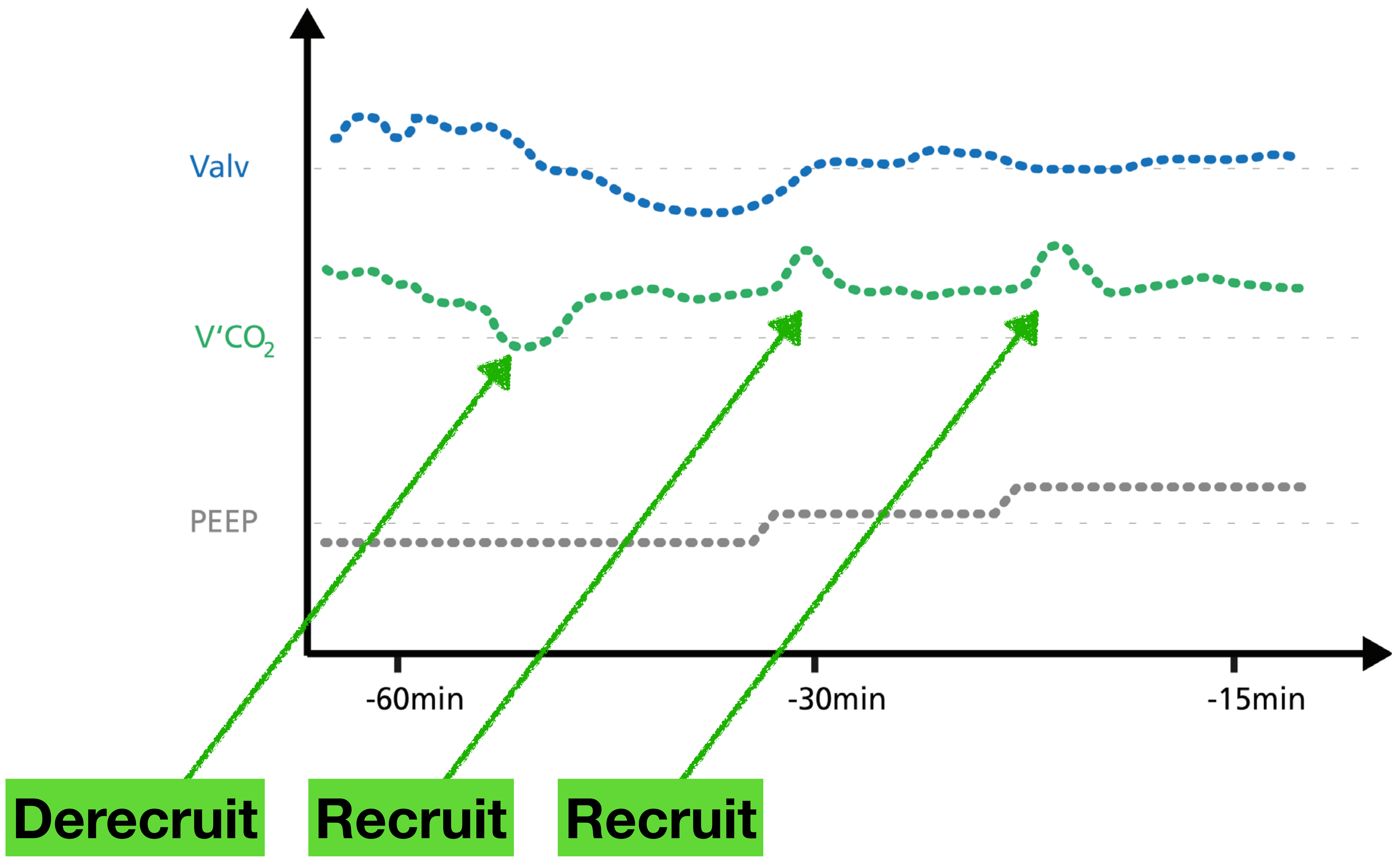


V’CO2トレンド：虚脱の発見

Volumetric CO_2 provides continuous monitoring to detect derecruitment and recruitment of alveoli.

Alveolar ventilation and $V'CO_2$ will first decrease if the lung derecruits, and will then stabilize again at equilibrium.

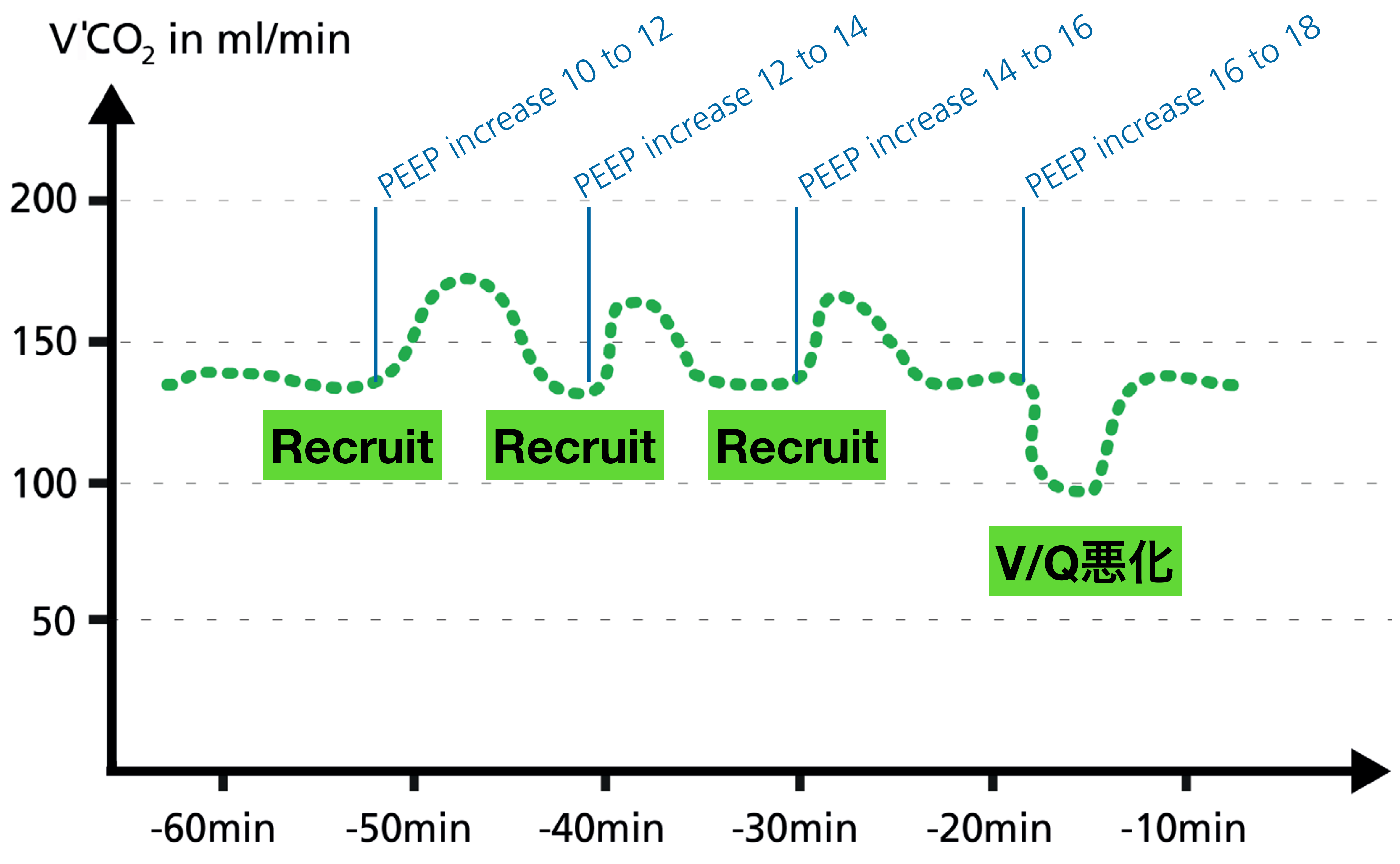
Recruitment, during, for example, a PEEP increase, can be detected by short $V'CO_2$ peaks before $V'CO_2$ returns to equilibrium.



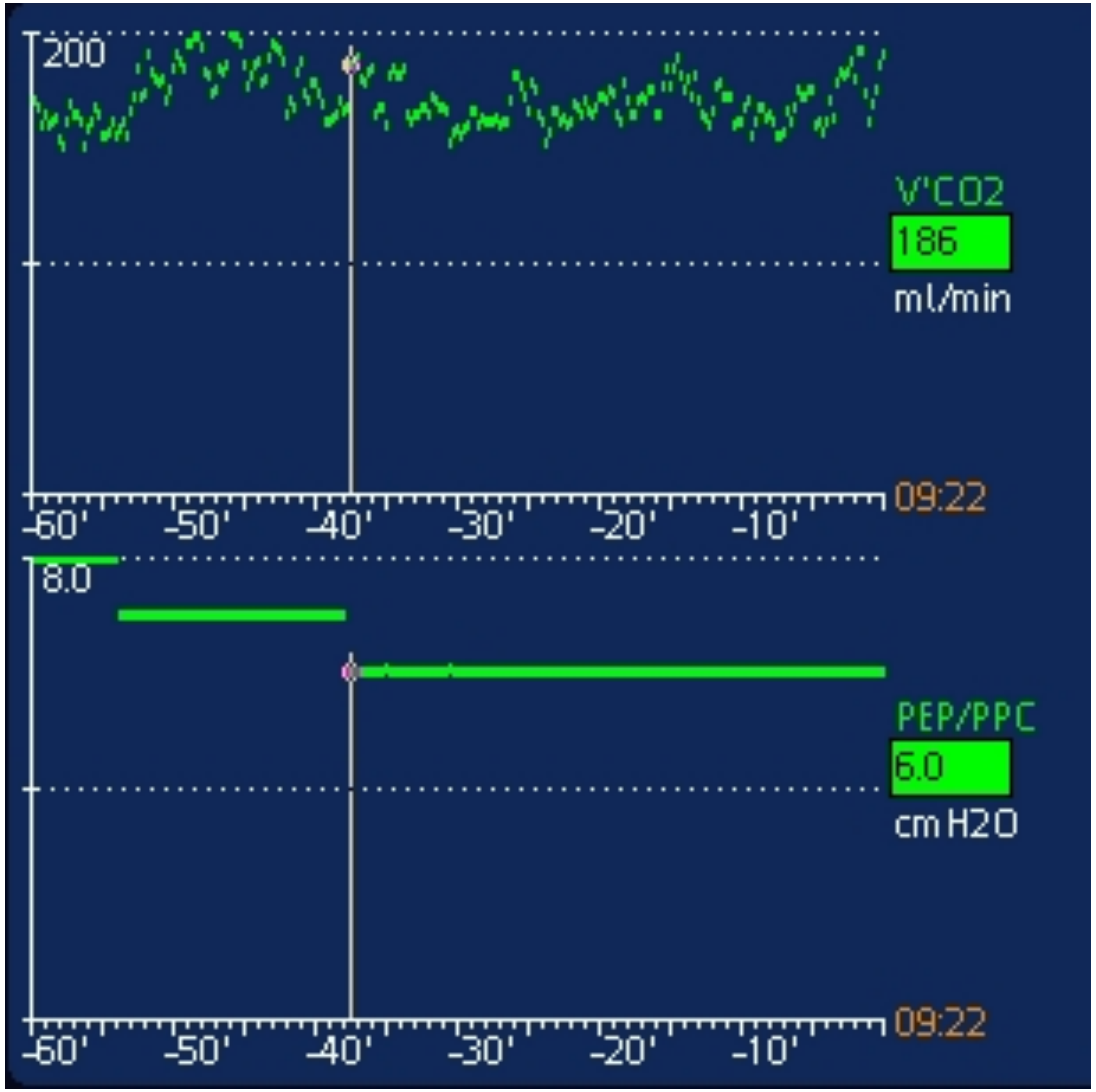
V’CO2トレンド：PEEP titration

When PEEP change is associated with an improving ventilation/perfusion ratio, V‘CO_2 shows a transient increase for a couple of minutes and then returns back to baseline, that is, in equilibrium with CO_2 production.

When PEEP change is associated with a worsening of the ventilation/perfusion ratio, V‘CO_2 transiently decreases for a few minutes and then returns to baseline.



PEEP titrationの実例

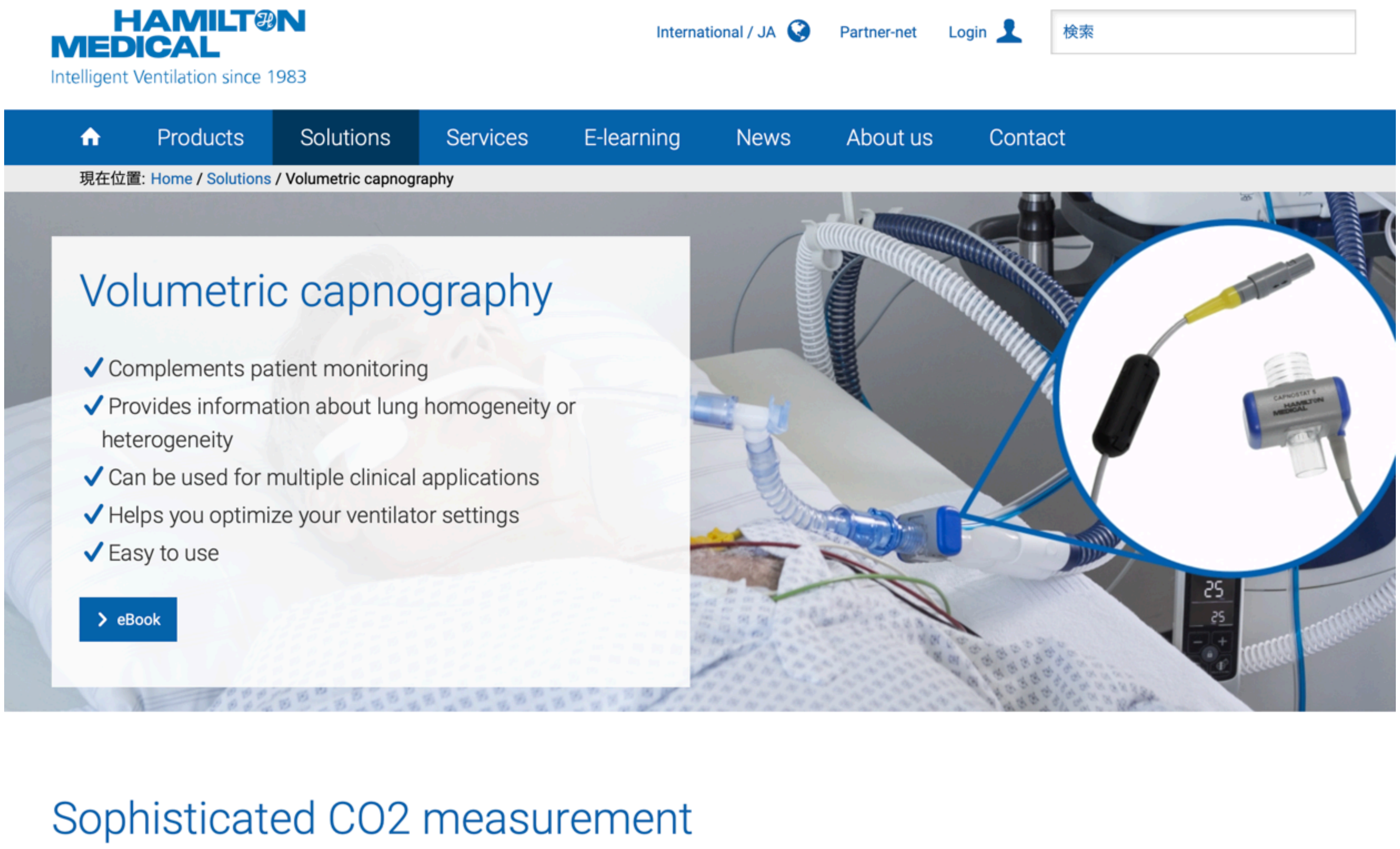


ゴール

- Volumetric capnographyとは何かを定義できる。
- Volumetric capnographyの波形の成り立ちを説明できる。
- CO_2産生から呼出までの過程を説明できる。
- Volumetric capnographyで得られるデータの解釈ができる。
- ベッドサイドで”使う”ことができる。

生理学を面白がろう

参考文献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✓ Easy to use
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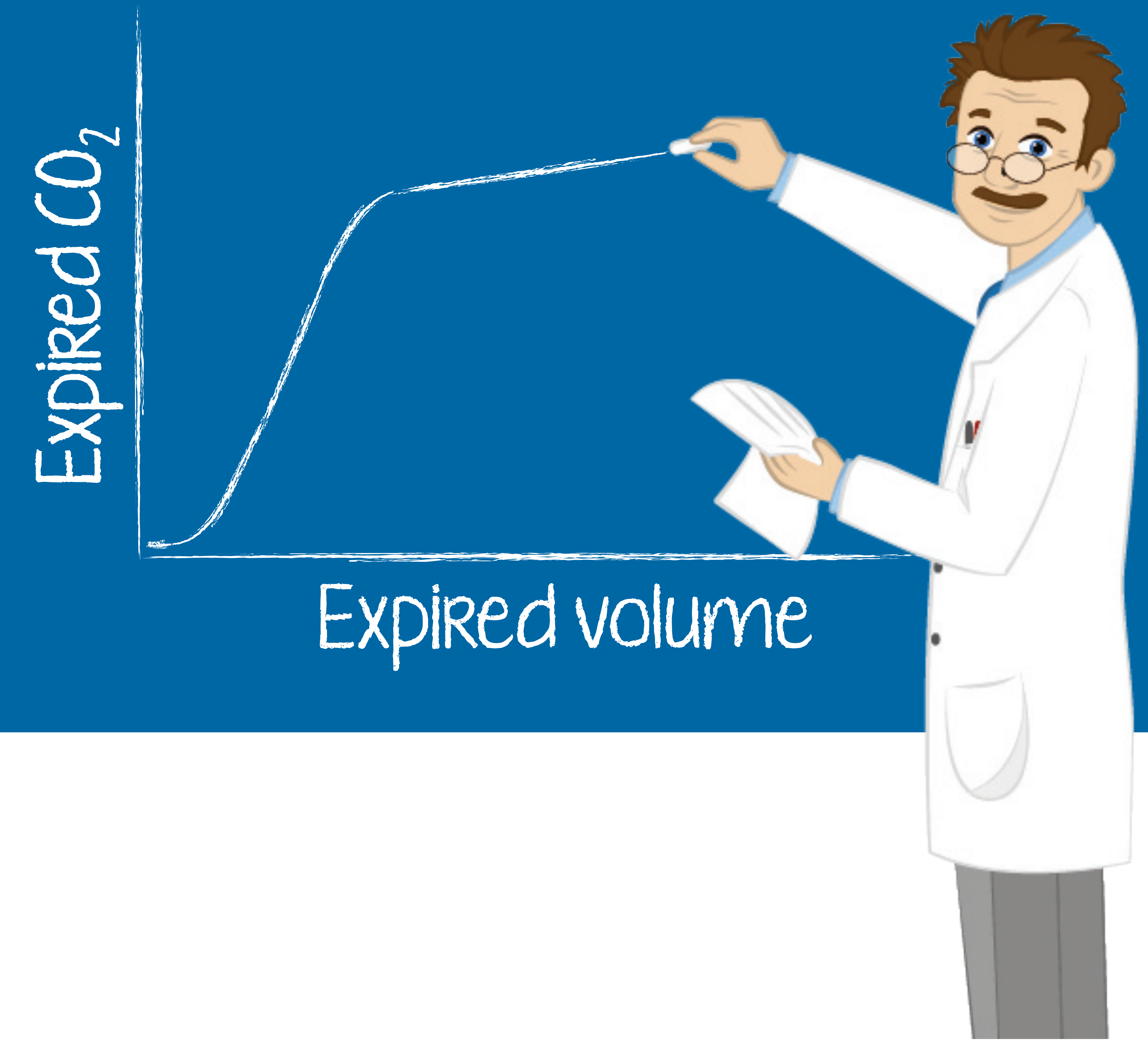

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