

## Closing Capacity Measurement during General Anesthesia

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A modification of the single-breath nitrogen closing volume (CV) test allows measurement of closing capacity (CC) during general anesthesia. In the modification, inspiration and expiration are mechanically produced by a hydraulically powered cylinder. For 14 awake, normal subjects, results of the CV test performed using this mechanical method differed than those obtained following spontaneous inspiration and expiration. Mean ( $\pm$ SE) CC's were 2.25 ( $\pm$ 0.15) and 2.42 l ( $\pm$ 0.14) ( $P < 0.01$ ) using spontaneous and mechanical methods, respectively. The slopes of Phase III of the CV traces were 2.24 ( $\pm$ 0.27) and 2.66 per cent  $N_2$  l ( $\pm$ 0.32) ( $P < 0.01$ ), respectively. To eliminate differences due to measurement technique, the modified CV test was used both before and during anesthesia with halothane in 70 per cent  $N_2$  in 11 normal, supine, spontaneously breathing subjects. CC's were 1.59 l ( $\pm$ 0.16) before and 1.54 l ( $\pm$ 0.15) during anesthesia ( $P > .5$ ). Mean functional residual capacities (FRC) by the closed-circuit helium method were 1.77 l ( $\pm$ 0.15) before and 1.45 l ( $\pm$ 0.17) during anesthesia ( $P < .001$ ). With CC unchanged and FRC decreased following induction, CC/FRC increased from 1.07 ( $\pm$ 0.08) to 1.37 ( $\pm$ 0.11) ( $P < .005$ ), suggesting increased small-airway closure during anesthesia. (Key words: Lung, airway closure; Ventilation, mechanical, airway closure.)

SMALL-AIRWAY CLOSURE has been suggested as one mechanism leading to the increase in alveolar-arterial oxygen gradient  $[P(A-a)_{O_2}]$  observed in patients during general anesthesia.<sup>1,2</sup> Airway closure, by reducing ventilation to gravity-dependent regions of the lung,

will produce areas with low ventilation-perfusion ( $\dot{V}/\dot{Q}$ ) ratios, leading to an enlarged  $P(A-a)_{O_2}$ . The closing volume (CV) test is thought to provide indirect measurement of the onset of airway closure. Closing capacity (CC) is the lung volume at which the onset of airway closure is detected. When the CC is larger than functional residual capacity (FRC), airway closure is thought to occur during normal tidal breathing, so impairing pulmonary gas exchange.<sup>3</sup>

Change in either CC or FRC, or both, will obviously affect their relationship. Previous studies have found FRC to be reduced following induction of anesthesia.<sup>4</sup>

Until recently there had been no report of CC measurement during general anesthesia in man. Hedenstierna *et al.* described a modified technique that allowed CC measurement in most but not all of 20 normal patients during mechanical ventilation with air, with anesthesia maintained by a thiopental drip and intermittent doses of fentanyl.<sup>4</sup> In addition to the fact that the technique is unsuitable for use either during anesthesia with an inhalation agent or during spontaneous ventilation, several major assumptions were made in its development that are, as discussed below, in disagreement with the literature.

We have developed a modification of the nitrogen method CV test for use during

### ABBREVIATIONS

CC	= closing capacity
CV	= closing volume
ERV	= expiratory reserve volume
FRC	= functional residual capacity
IC	= inspiratory capacity
$P(A-a)_{O_2}$	= alveolar-arterial oxygen pressure difference
RV	= residual volume
TLC	= total lung capacity
VC	= vital capacity
$\dot{V}/\dot{Q}$	= ventilation-perfusion ratio

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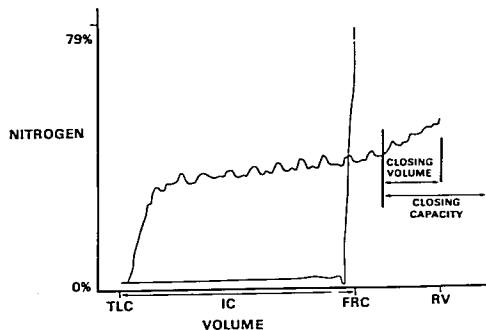


FIG. 1. Tracing obtained in CV test in which  $O_2$  inspiration begins at FRC instead of RV. Subject breathes room air until switched into  $O_2$  source at FRC, inspires IC breath to TLC, then expires VC breath to RV. CV is volume between point of terminal slope change and RV.  $CC = CV + RV$ . RV is determined independently.

general anesthesia. This paper describes the modified test, its validation, and its application during anesthesia.

### Methods

We used a modification of the CV test in which inspiration of oxygen is initiated at FRC instead of RV as in the standard test.<sup>5</sup> The FRC modification is summarized in figure 1. This FRC version is known to produce results different from those obtained with the RV version.<sup>§</sup> They include increases in CC, the slope of Phase III of the CV trace, and the size of the cardiogenic oscillations.

To allow CC measurement during anesthesia in the absence of patient cooperation, a hydraulic pump (fig. 2) was included in the breathing circuit. This produced the necessary inspiratory capacity (IC)  $O_2$  inspiration, and vital capacity (VC) expiration, at controlled flow rates. Inspiratory flow rate was 0.3 l/sec, expiratory 0.25 l/sec. These were chosen because they met established criteria<sup>6</sup> and were tolerated by awake subjects. Except for the hydraulic pump in the patient circuit, the apparatus used for CC measurement was as has been suggested.<sup>6</sup> The sampling head of the nitrogen analyzer was modified to eliminate the interfering effects of halogenated anesthetics.<sup>7</sup> This modified sampling head was used throughout the study.

§ McCarthy DS, Craig DB, unpublished observations.

### VALIDATION STUDY

Measured values of CC obtained using the mechanically induced inflation and deflation were compared with values obtained during spontaneous inspiration and expiration in 14 healthy supine subjects aged 21-64 years (mean 42 years). Spontaneous inspiration or mechanical inflation with  $O_2$  always began at FRC. Because we found awake subjects unable to tolerate inflation to total lung capacity (TLC), an IC breath to 90 per cent of the previously determined full IC was used in both mechanical and spontaneous methods. In the mechanical method, patients breathed spontaneously until they were switched into the test circuit at FRC. Inflation with  $O_2$  to 90 per cent IC was followed by deflation back past FRC to the previously determined residual volume (RV). The sequence of testing was varied in a random fashion. Tracings were analyzed according to the criteria previously suggested.

### ANESTHESIA STUDY

Eleven patients, all ASA physical status I, scheduled for elective extremity surgery were studied. Patients were interviewed and examined by one of the investigators and specific consent for the study was obtained. Mean age was 28 years (range 20-50); six patients were cigarette smokers; eight were male and three female. None was obese. All studies were performed with the patients supine.

Awake control measurements were made in the operating room prior to induction of anesthesia. FRC was measured by the closed-circuit helium technique. CC was measured using the mechanical method as described. The mean values from two or three satisfactory tracings were used.

Anesthesia was induced following the control studies, about 40 minutes before the operation began. *d*-Tubocurarine, 3 mg, and atropine, 0.4 mg, were administered intravenously. Following preoxygenation and administration of thiopental, 4 mg/kg, and succinylcholine, 1 mg/kg, the trachea was intubated with a cuffed tracheal tube. Anesthesia was maintained with halothane in 70 per cent nitrogen, 30 per cent oxygen. Ventilation was assisted manually until spontaneous respiration resumed. Twenty minutes after induction of anesthesia, FRC was measured by the closed-circuit helium technique, with appropriate corrections made for the interfering effects of halothane and O<sub>2</sub>.<sup>6</sup> CC was measured as in the control state. Except for the mechanical inflations during CC measurements, respiration was spontaneous. Following completion of the studies, the inspired gas mixture was changed to N<sub>2</sub>O and O<sub>2</sub> with halothane, and the operation commenced.

FIG. 2. Diagram (not to scale) of hydraulic device used in modified CV test. Power cylinder\* is linked to passive cylinder.† A, in or out stroke is produced by directing compressed gas to either side of air chamber of power cylinder. B, rate control, independent for in and out strokes, is by variable oil bleeds between oil phase of power cylinder. C, patient is connected to O<sub>2</sub>-filled passive cylinder. Also in patient circuit (not shown) are positive (+40 cm H<sub>2</sub>O) and negative (-18 cm H<sub>2</sub>O) pressure relief valves. D, Connection to spirometer. Correction is made for the different volume characteristics of the two sides of the passive cylinder.

\* Schrader MS2-A1, Tandem air-oil cylinder, Scovill Fluid Power Division, Wake Forest, North Carolina.

† Alkon D. Style 1503, with chrome-plated rod for "service without lubrication." Alkon Products, Hawthorne, New Jersey.

## Results

Results of the validation study comparing values obtained by spontaneous and mechanical methods are summarized in table 1. Inspiratory and expiratory lung volumes were the same using both methods. CC was detected at a higher lung volume using the mechanical method. This is also reflected by the increases in CC/FRC and FRC-CC. The slope of Phase III of the CV trace was also greater using the mechanical method, while there was no change in the slope of Phase IV or in the size of the cardiogenic oscillations.

The results for the 11 patients in the anesthesia study are summarized in table 2. Inspiratory and expiratory lung volumes were the same before and during anesthesia. Although not reported in the table, inspiratory (0.3 l/sec) and expiratory (0.25 l/sec) flow rates were identical in the two parts of the study. CC was unchanged following induction of anesthesia, while FRC decreased significantly. As a result of the reduced FRC, both FRC-CC and CC/FRC increased significantly. The slope of Phase III of the CV trace decreased significantly following induction of anesthesia, while the size of the cardiogenic oscillations increased.

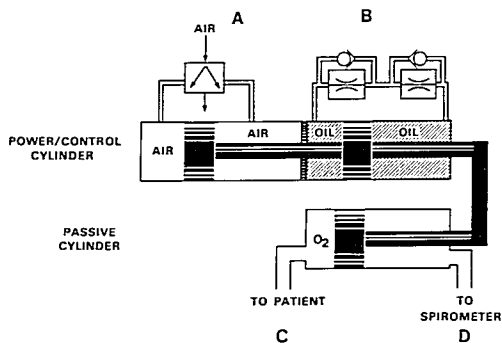


TABLE 1. Validation Study: Single-breath  $N_2$  CV Test, FRC Method (n = 14; Mean  $\pm$  SE)

	Spontaneous Inspiration/ Expiration	Mechanical Inflation/ Deflation	Signifi- cance*
Inspiratory capacity (IC) (l)	3.74 $\pm$ .20	3.83 $\pm$ .18	NS
Expiratory reserve volume (ERV) (l)	.59 $\pm$ .08	.60 $\pm$ .08	NS
Closing capacity (CC) (l)	2.25 $\pm$ .15	2.42 $\pm$ .14	$P < .01$
CC/FRC	1.14 $\pm$ .06	1.25 $\pm$ .06	$P < .01$
FRC-CC (l)	-.27 $\pm$ .11	-.44 $\pm$ .12	$P < .01$
Phase III (per cent $N_2$ /l)	2.24 $\pm$ .27	2.66 $\pm$ .32	$P < .02$
Phase IV (per cent $N_2$ /l)	10.51 $\pm$ 1.07	9.84 $\pm$ .94	NS
Cardiogenic oscillations (per cent $N_2$ /l)	1.67 $\pm$ .24	1.53 $\pm$ .28	NS

\* By t test for paired data.

### Discussion

The results of the validation study clearly indicate that measurements obtained using our mechanical-inflation technique differed from those obtained following spontaneous inspiration and expiration. These results are in disagreement with those of Hedenstierna *et al.*, who found that exhalation through a flow regulator did not alter CV in five awake subjects.<sup>4</sup> Except for the small number of subjects in the earlier study, no other potential explanation for these important differences is apparent.

The observed increase in CC with the mechanical technique in the present study may indicate that small-airway closure actually began at a higher lung volume, or airway closure could have started at the same lung volume but have merely been detected at a higher volume.

Using the mechanical technique, negative airway pressures exist, of necessity, between FRC and RV. If this negative pressure is transmitted to the small airways, the transmural pressure (pleural-airway) will be

altered, favoring airway closure. However, in some subjects, CC was greater than FRC using both methods, so negative airway pressures were not present at CC. Kaneko *et al.* have shown that changes in the tracer gas gradient in the lung during CC measurement can alter the measured CC, although the actual point of airway closure is unchanged.<sup>5</sup> In addition, it is possible that the pattern of sequential emptying of different lung regions may have changed during the mechanical maneuver, and that this produced the change in measured CC. These possibilities require further exploration, using techniques that will allow direct examination of inspired gas distribution.

The positive slope of Phase III of the CV trace is thought to result from both regional and stratified inhomogeneity.<sup>6</sup> Regional inhomogeneity results from time-constant differences between different lung regions and gravity-determined differences in regional volume changes during the breathing maneuvers of the CV test. Stratified inhomogeneity is thought to be due to incomplete diffusion mixing in the peripheral lung units. The increased Phase III slope may have resulted from increased inhomogeneity due to both factors, or only one. The size of the cardiogenic oscillations is thought to reflect primarily interregional concentration differences and the cardiac stroke volume.<sup>10</sup> The observed decrease in size of the oscillations may therefore be due to changes in either factor or both.

Regardless of the reasons for the differences, we conclude that since the results of the spontaneous and mechanical techniques indicated they are not equivalent, it would only be valid to compare intraoperative measurements made by the mechanical technique with similar measurements obtained preoperatively. Accordingly, the same technique for CC measurement was used in both awake and anesthetized subjects. In contrast, Hedenstierna *et al.* measured CC following spontaneous inspiration and expiration before anesthesia, but after a controlled inflation during anesthesia.<sup>4</sup> Based on our data, this difference would be expected to produce an increased CC value during anesthesia, due to the technique of measurement alone. In addi-

TABLE 2. Functional Residual Capacity and Closing Capacity during Anesthesia (n = 11; Mean  $\pm$  SE)

	Vital Capacity (l)	Expiratory Reserve Volume (l)	Functional Residual Capacity (l)	Closing Capacity (l)	FRC-CC	CC/FRC	Slope Phase III (Per Cent $N_2$ )	Cardiogenic Oscillations (Per Cent $N_2$ )
Awake	3.88 $\pm$ .24	0.62 $\pm$ .08	1.77 $\pm$ .15	1.89 $\pm$ .16	-.11 $\pm$ .13	1.07 $\pm$ .08	1.73 $\pm$ .24	1.07 $\pm$ .16
Anesthesia	3.90 $\pm$ .24	0.63 $\pm$ .08	1.45 $\pm$ .17	1.84 $\pm$ .15	-.39 $\pm$ .09	1.37 $\pm$ .11	1.19 $\pm$ .20	2.04 $\pm$ .27
Significance*	NS	NS	$P < .001$	NS	$P < .01$	$P < .005$	$P < .001$	$P < .005$

\* By t test for paired data.

tion, Hedenstierna *et al.* began  $O_2$  inspiration at RV before, and FRC during, anesthesia, while measuring CC.  $O_2$  inspiration from FRC has itself been shown to increase the measured CC.<sup>5</sup> The two factors combined, the controlled inflation and the FRC start of inspiration, could be expected to produce large artifactual increases in measured CC.

Our finding that CC was unchanged following induction of anesthesia is an important observation that confirms previous assumptions. This constancy of CC is not unexpected. Airway closure is thought to occur when the net forces promoting collapse of small airways exceed the net forces keeping these airways open.<sup>11</sup> Forces promoting patency include the basic structural components of the airway, but are related primarily to the supporting effects of surrounding lung tissues. In normal lungs, forces promoting airway closure are thought to consist mainly of positive intrapleural pressures, which can exist in a variety of circumstances.<sup>11</sup> It must also be recalled that the CV test involves a VC expiration during which the point of onset of airway closure is detected. We recognize no reason why, shortly after induction of general anesthesia in normal subjects and during the VC expiration, the lung volume at which small-airway closure begins should differ from the lung volume at which this occurs in the awake state. In order for CC to change, there would have to be a change in the basic structural properties of the lung affecting the balance of forces promoting and opposing small-airway patency.

Our observation of an unchanged CC can be considered valid only in the circumstances

studied—within 40 minutes of induction of anesthesia in spontaneous breathing, healthy patients. It remains possible that with prolongation of anesthesia, controlled ventilation, and fluid infusion, or in patients who have cardiorespiratory abnormalities, different results will be found. Our basic observation remains, however, that CC did not change following induction of anesthesia.

The significant decrease in FRC following induction of anesthesia agrees with findings in previous studies in anesthetized patients breathing spontaneously.<sup>1,2</sup> With CC unchanged, the decreased FRC is the important factor determining the effect of airway closure on pulmonary gas exchange. Airway closure is thought to affect gas exchange by altering distribution of ventilation during tidal breathing. The increase in CC/FRC ratio suggests that airways were closed throughout more of tidal breathing during anesthesia. This would lead to decreased  $\dot{V}/\dot{Q}$  relationships in gravity-dependent regions of the lung.

The observed decrease in the slope of Phase III during anesthesia is in agreement with previous findings of Rehder *et al.* using different measurement techniques.<sup>12</sup> This suggests a more uniform distribution of the IC breath of  $O_2$  and supports the earlier conclusion that ventilation distribution is more uniform during anesthesia.<sup>12,13</sup> The increase in the size of the cardiogenic oscillations is, however, contrary to findings in the earlier studies.<sup>12</sup> Since cardiogenic oscillations reflect interregional inhomogeneity, while the Phase III slope is due to both inter- and intraregional inhomogeneity, these findings are compatible. Ventilation-distribution may have been more

uniform within lung regions but less uniform between them.

A word of caution about the ease of application of our modified CV test is necessary. Many awake patients were unable to tolerate the inflation and deflation that was necessary to allow CC measurement. While complete studies were obtained in 11 patients, CC measurement was impossible in six additional patients who were unable to maintain an open glottis or leak-free mouthpiece seal during mechanical inflation. We did not study any subject who had significant pulmonary disease, but have found previously that CC measurement may be impossible in such patients due to a steeply rising Phase III slope, which masks any terminal slope change.

In summary, we have developed a modification of the single-breath nitrogen CV test that allows measurement of CC during general anesthesia in man. For awake normal subjects, results of this mechanical-inflation technique differed from those obtained with a technique with spontaneous inspiration and expiration. Using the mechanical technique both before and during anesthesia, we found CC unchanged shortly after induction of general anesthesia in healthy patients. While CC did not change, FRC decreased significantly, increasing the CC/FRC ratio. Further studies are needed to correlate changes in CC/FRC and  $P(A-a)_{O_2}$  following induction of anesthesia.

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