Anesthesiology 2010; 113:1370–5

Inhalation Anesthesia Increases V/Q Regional Heterogeneity during Spontaneous Breathing in Healthy Subjects

Sven Nyrén, M.D.,* Peter Radell, M.D., Ph.D.,† Margareta Mure, M.D., Ph.D.,‡ Johan Petersson, M.D., Ph.D.,§ Hans Jacobsson, M.D., Ph.D.,‖ Sten G. E. Lindahl, M.D., Ph.D.,# Alejandro Sánchez-Crespo, M.Sc., Ph.D.**

ABSTRACT

Background: The underlying mechanism for the increased alveolar-arterial oxygen tension difference resulting from almost all forms of general anesthesia is unknown. We hypothesized that inhalation anesthesia influences the intrapulmonary distribution of ventilation (V) and perfusion (Q), leading to less advantageous V/Q matching.

Methods: Ten healthy volunteers were studied in supine position on two separate occasions, once awake and once during mild anesthesia (sevoflurane inhalation) with maintained spontaneous breathing. On both occasions, the distribution of V and Q were simultaneously imaged using single photon emission computed tomography. V was tagged with [^{99m}Tc]-labeled carbon particle aerosol and Q with [^{113m}In]-labeled macroaggregates of human albumin. Atelectasis formation during anesthesia was prevented using low concentrations of oxygen in inhaled air.

Results: Mean V and Q distributions in the ventral-to-dorsal direction, measured in 20 equally spaced volumes of interest and in three regions of interest of equal volume, did not differ between conditions. Anesthesia, when compared with the awake state, significantly decreased the total heterogeneity of the Q distribution ($P = 0.002$, effect size 1.16) but did not alter V ($P = 0.37$, effect size 0.41). The corresponding V/Q total heterogeneity was higher under anesthesia ($P = 0.002$, effect size 2.64). Compared to the awake state, the V/Q frequency distribution under anesthesia became wider ($P = 0.009$, 1.76 effect size) with a tendency toward low V/Q ratios.

Conclusion: Inhalation anesthesia alone affects Q but not V, suggesting that anesthesia has a direct effect on the active regulatory mechanism coordinating Q with V, leading to less favorable V/Q matching.

What We Already Know about This Topic

❖ Anesthesia is associated with deterioration in pulmonary gas exchange. The underlying mechanism is not fully understood.

What This Article Tells Us That Is New

❖ In healthy volunteers, inhalation anesthesia affects lung perfusion (Q) but not ventilation (V), increasing intrapulmonary heterogeneity in V/Q distribution.

ALMOST all forms of general anesthesia, including inhalation anesthesia, are associated with deterioration in pulmonary gas exchange.[1] Maintained coordination of regional lung perfusion (Q) and ventilation (V) is crucial for optimal blood oxygenation. The underlying mechanism of this function is still not fully understood. Several determinants of regional Q have been reported in animal studies, among them, lung vascular structure,[2] differences in vessel conductance between lung regions,[3,4] gravity[5] and hypoxic

* Clinical Research Fellow, Department of Molecular Medicine and Surgery, Karolinska Institutet, Stockholm, Sweden, and Department of Radiology, Karolinska University Hospital, Stockholm, Sweden. ‖ Professor, Department of Molecular Medicine and Surgery, Karolinska Institutet, and Departments of Nuclear Medicine and Radiology, Karolinska University Hospital. † Associate Professor, Department of Physiology and Pharmacology, Karolinska Institutet, and Head, Department of Pediatric Anesthesiology and Intensive Care, Karolinska University Hospital. ‡ Associate Professor, Department of Physiology and Pharmacology, Karolinska Institutet, and Department of Anesthesiology and Intensive Care, Karolinska University Hospital. § Anesthesiologist, Department of Physiology and Pharmacology, Karolinska Institutet, and Department of Anesthesiology and Intensive Care, Karolinska University Hospital. # Professor, Department of Physiology and Pharmacology, Karolinska Institutet, and Research Director, Karolinska University Hospital. ** Hospital Physicist, Department of Oncology-Pathology, Karolinska Institutet, and Department of Nuclear Medicine, Karolinska University Hospital.

Received from the Department of Molecular Medicine and Surgery, Karolinska Institutet, Stockholm, Sweden, and Karolinska University Hospital, Stockholm, Sweden. Submitted for publication April 21, 2010. Accepted for publication September 1, 2010. Supported by the Swedish Heart and Lung Foundation (Stockholm) Grant no. 20040689. None of the authors has any financial relationship with a commercial entity that has an interest in the subject of this study.

Address correspondence to Dr Nyrén: Department of Radiology, Karolinska University Hospital, Solna, SE-171 76 Stockholm, Sweden. sven.nyren@karolinska.se.

pulmonary vasoconstriction.[6] In addition, human studies have shown that selective nitric oxide synthesis[7] and posture[8,9] also seem to influence Q with a more uniform distribution in the ventral-to-dorsal direction in prone *versus* supine position. This effect was also observed in healthy volunteers under general anesthesia with mechanical ventilation.[10] Raised intrathoracic pressure from continuous positive airway pressure causes a shift in pulmonary blood flow toward dependent parts of the lungs, which may influence V/Q matching.[9,11] The regional distribution of V is more likely regulated by passive mechanisms, such as variations of alveolar compliance in different parts of the lungs,[12] inspiration rate, and regional pleural pressure.[1,13]

During inhalation anesthesia with spontaneous breathing, there is increased passage of mixed venous blood through the lungs that is believed to be, at least partly, related to formation of atelectasis.[14–16] Atelectasis formation is a known phenomenon currently considered an effect of a decreased functional residual capacity[15,17–19] and high oxygen concentration in the inhaled gas during anesthesia induction.[14] In addition, a recent report[20] has also shown a vasoconstrictive effect from halothane and other volatile anesthetics. However, researchers have also shown that inhalation anesthetics inhibit hypoxic pulmonary vasoconstriction in humans[6,16,21] and animals.[22] These results suggests that the overall effect of inhalation anesthesia on pulmonary circulation is limited and with no apparent regional effects.[21] On the other hand, the underlying mechanisms for increased dead space[22–24] and impaired oxygenation during anesthesia[24] are still unclear.[16] The direct effect of inhalation anesthesia on the regional distribution of the V and Q studied *in vivo* has, to our knowledge, not been studied in humans. This combination of factors may contribute to the resulting passage of mixed venous blood through the lungs. Furthermore, in acute respiratory distress syndrome, where increased shunt and dead space result in an abnormal V/Q ratio distribution,[25] the addition of inhalation anesthetics could be detrimental. In the current investigation, we hypothesized that facial mask mild inhalation anesthesia would lead to a change in the distribution of V/Q ratios within the lung.

We previously developed a quantitative scintigraphic method using single photon emission computed tomography (SPECT) that simultaneously measures regional V and Q.[26,27] In the current study, we used this method to compare regional V and Q in healthy subjects breathing spontaneously while awake and during inhalation anesthesia.

Materials and Methods

Subjects

Ten healthy, nonsmoking volunteers (5 men, 5 women; mean age 25 yr, range 20–34 yr) were studied. All were of normal weight (mean 68 kg, range 58–81 kg) and height (mean 1.73 m, range 1.58–1.81 m). The study was approved by the local ethics and radiation protection committees. Informed, written consent was obtained from all participants.

Radiopharmaceuticals

Approximately 50 MBq of [^{113m}In]-labeled macroaggregates of human albumin (TechneScan LyoMAA, Mallinckrodt Medica, Petten, The Netherlands) was used as tracer for Q. Simultaneously, approximately 50 MBq of [^{99m}Tc]-labeled Technegas (Tetley Manufacturing Ltd., Sydney, Australia) was used as tracer for V.

Anesthesia

To avoid excessive saliva secretion, 0.1 mg glycopyrron was injected. Standard monitoring equipment for electrocardiography and pulse oximetry was applied. Inhaled oxygen fractions, end-tidal concentration of carbon dioxide, pulse oximetry, tidal volume, minute ventilation, respiratory rate, and expired concentration of the anesthetic agent were monitored continuously in accordance with clinical practice.

Anesthesia was induced by inhalation of sevoflurane through a tight fitting facemask. In each subject, anesthesia was continued under spontaneous breathing for approximately 20 min with sufficient sevoflurane to reach a minimum alveolar concentration value of approximately 1. Age correction was performed so that slightly different end-tidal concentration of sevoflurane between subjects was obtained (average 2.9 ± 1.4%). During anesthesia, a maximum of 500 ml of a balanced acetate solution were infused intravenously while inhaled and exhaled gases were analyzed continuously (DATEX AS/3; Datex-Ohmeda Division, Instrumentarium Corp., Helsinki, Finland).

Because the major focus of this investigation was to isolate the effect of anesthetics alone on the V and Q distribution, atelectasis formation during anesthesia was prevented by keeping low concentrations of oxygen in inhaled air (0.3).

Experimental Design

Volunteers fasted for 6 h before examinations. Each subject was examined on two different days using SPECT, once awake and once during inhalation mask anesthesia and spontaneous breathing. The order of the investigations was randomized by lottery. Five subjects were investigated first awake and then anesthetized and the other five in the reverse order. At least 3 days (mean 9 days) elapsed between examinations. The subject was, on both occasions, examined in the supine posture. The steady state during anesthesia was reached at approximately 20 min after induction (range 18–25 min). Technegas was administered via facial mask while LyoMAA was administered intravenously. After administration of the radiotracers, sevoflurane delivery was terminated and anesthesia ended. The mean duration of anesthesia was 33 min (range 25–44 min). SPECT image acquisition started as soon as the patient regained complete consciousness. At completion of the scan, the subject was kept a few hours for recovery before hospital discharge. The procedure during the awake state mimicked that during anesthesia except for the administration of the anesthetic drug.

SPECT Scan

Image acquisition using SPECT scans was performed using a three-headed Triad XLT γ camera (Trionix, Twinsburg, OH) with middle energy collimators. Emission data were collected in 72 projections during a 360° rotation with a total acquisition time of 25 min. A matrix size of 128 × 128 and a voxel size of 3.6 mm^3 were used. Photon emission data were registered simultaneously in four energy windows,[26] two primary windows centered at 140 keV (for V) and 392 keV (for Q) and two secondary windows placed beneath each primary window for scatter corrections. After registration of emission images, a 15-min transmission scan was made with a [^{99m}Tc]-filled line source. These images were used for attenuation correction of the emission images[26] and as anatomical reference. Filtered back projection was used for image reconstruction.

Data Analysis

After image reconstruction, SPECT data for each isotope were corrected for scattering, attenuation, activity decay, and organ outline.[26] In addition, the root-mean-square noise component was calculated and subtracted from each dataset.[10] For each subject, corrected and noise-free images were pixel-wise normalized to the total activity within the lungs for V and Q, respectively. V/Q ratios were obtained as the quotient between the fraction of V and the fraction of Q in each pixel.

In each individual, the regional V, Q and V/Q ratio distribution were first analyzed in three compartments of equal volume in the anterioposterior direction. They were then analyzed in 20 isogravitational planes along the ventral-to-dorsal axis. A two-tailed, paired Student *t* test with Bonferroni correction was used for significance testing of the regional distribution of the V, Q, and V/Q between awake and anesthetized conditions (Microsoft Office Excel 2003; Microsoft Corporation, Redmond, WA). A *P* value less than 0.016 was considered statistically significant.

The frequency distribution of V/Q ratios was compared between awake and anesthetized conditions. A Gaussian function was fitted using a least-squares method to the V/Q ratio distribution for both the awake and anesthetized states and the full width at half maximum calculated. Differences in full width at half maximum of V/Q ratio distributions between awake and anesthetized states were pair-wise analyzed using a two-tailed, paired Student *t* test with a significance level set at 0.05.

The heterogeneities of the regional distribution of the V, Q, and V/Q ratios were estimated using a variance analysis.[10] The global lung heterogeneity (SS_{total}) was obtained as the sum of squares of the pixel-wise differences from the entire lung average value respectively for V, Q, and V/Q ratio. Thereafter, the average pixel value within each isogravitational plane in the ventral-to-dorsal direction was calculated. The sums of squares of the pixel-wise deviations from mean in each plane were added ($SS_{residual}$), respectively, for V, Q, and V/Q ratio. Finally, the heterogeneity of V, Q, and V/Q explained by the vertical direction ($SS_{vertical}$) was respectively calculated by subtracting $SS_{residual}$ from SS_{total}. A two-tailed Student *t* test was used to compare SS_{total} and $SS_{vertical}$ between awake and anesthetized states, respectively, for V, Q, and V/Q. A *P* value less than 0.05 was considered statistically significant.

Table 1. Subject Variables during Mild Anesthesia

Variable	Mean ± SD
Arterial blood pressure, mmHg	—
Systolic	104 ± 11
Diastolic	67 ± 8
Heart rate, min^{-1}	74 ± 12
Fraction of inhaled oxygen, %	35 ± 2
End-tidal carbon dioxide, %	4.4 ± 0.7
Saturation of carbon oxide in peripheral blood, %	97 ± 1
Tidal volume (expired), ml	292 ± 158
Respiratory rate, min^{-1}	24 ± 5
Minute volume, l	5.7 ± 1.3
End-tidal concentration sevoflurane, %	2.9 ± 1.4

Mild anesthesia (sevoflurane inhalation) with maintained spontaneous breathing was used.

Results

Physiologic Variables

Physiologic variables recorded during anesthesia are shown in table 1. During the awake state, mean ± SD systolic blood pressure was115 ± 8 mmHg, higher than during anesthesia ($P = 0.002$). Diastolic blood pressure was 69 ± 6 mmHg and did not differ between states ($P = 0.191$). Heart rate during the awake condition was 61 ± 6 min^{-1}, lower than that observed during anesthesia ($P = 0.016$).

Regional Distribution of V, Q, and V/Q

The regional distribution of V and Q did not show any significant difference along the ventral-to-dorsal direction between the anesthetized and awake states when comparing equal lung volumes of interest, as shown in table 2. This finding was also observed in the 20 isogravitational planes

Table 2. Regional Mean ± SD Distribution of Lung Ventilation *vs.* Perfusion

	Location within Lung		
Variable	Ventral 1/3	Mid 1/3	Dorsal 1/3
V, %	—	—	—
Awake	24.7 ± 2.5	32.7 ± 1.0	41.5 ± 3.4
Anesthesia	23.5 ± 4.6	31.3 ± 3.4	44.5 ± 4.9
P value	0.18	0.40	0.13
Q, %	—	—	—
Awake	26.4 ± 2.3	33.0 ± 0.8	39.3 ± 3.2
Anesthesia	25.3 ± 2.0	33.0 ± 2.1	40.9 ± 3.9
P value	0.08	0.87	0.20

Mild anesthesia (sevoflurane inhalation) with maintained spontaneous breathing was used. All physical examinations were made with the subject in supine position. *P* values refer to awake *vs.* anesthetized state.

Q = perfusion; V = ventilation.

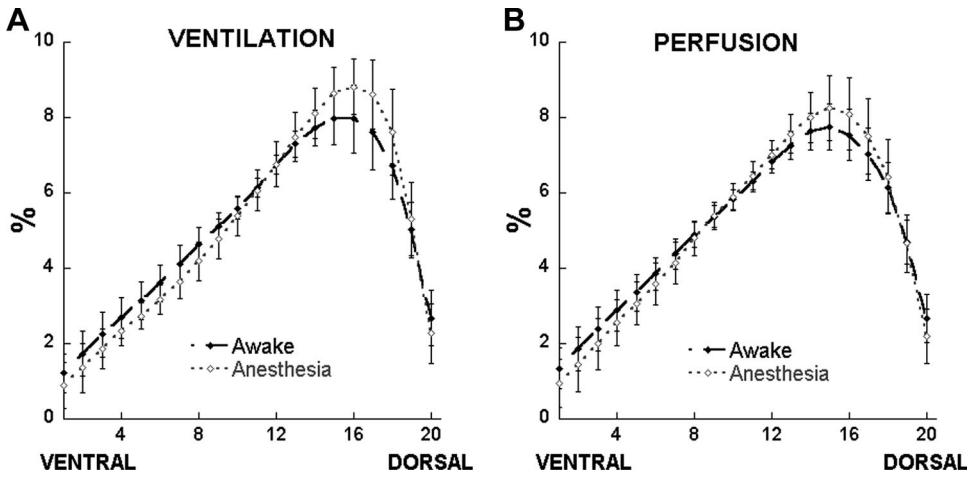

Fig. 1. The relative regional distribution of (*A*) ventilation (V) and (*B*) perfusion (Q) in the ventral-to-dorsal direction when subjects are in supine position. Data (mean ± SD) are based on twenty equally spaced volumes of interest. No significant differences were observed between conditions for V and Q.

illustrated in figure 1, which shows a dependent V and Q distribution in anesthetized and awake states. The width of the lung frequency distribution of V/Q ratios, expressed as full width at half maximum, was significantly larger during anesthetized *versus* awake states, 0.77 ± 0.12 and 0.57 ± 0.12, respectively ($P = 0.009$). The V/Q ratio frequency distribution under awake conditions was symmetric at V/Q = 1.0 (fig. 2). However, under inhalation anesthesia, there is a clear broadening of the V/Q ratio frequency distribution toward lower ratio values with maximum at V/Q = 0.9 (fig. 2).

Variance Analysis of the Regional Distribution of V, Q, and V/Q

The total and vertical variances (SS_{total}, $SS_{vertical}$) in ventilation distribution were not altered between awake *versus* anesthetized states (table 3). However, the variances (SS_{total}, $SS_{vertical}$) in the perfusion distributions decreased during anesthesia when compared to the awake state (table 3). This, however, resulted in increased variance of V/Q (SS_{total}, $SS_{vertical}$) during anesthesia.

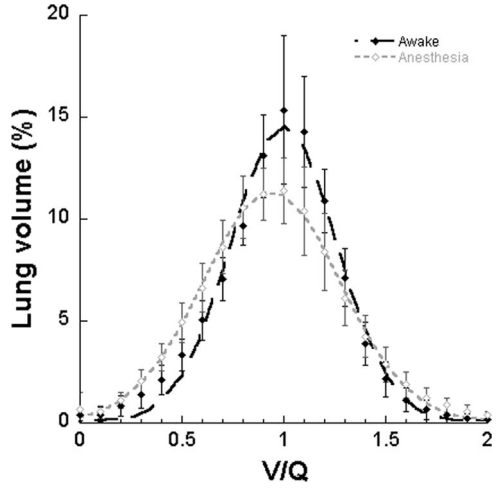

Fig. 2. The experimental points represent the frequency distribution of ventilation (V) and perfusion (Q) ratios (V/Q) along the entire lung volume in the awake and anesthetized state. Data (mean ± SD) for each condition were fitted to a Gaussian function using least-squares method.

Discussion

As related to healthy individuals, the main findings of this study are that the V and Q relative distribution along the ventral-to-dorsal direction is not significantly altered between awake and inhalation anesthesia conditions. In addition, regional heterogeneity of the V distribution is unaltered between conditions whereas it decreases with inhalation anesthesia for the Q distribution. Finally, inhalation anesthesia increases V/Q ratio regional heterogeneity and causes a widening in the frequency distribution with a tendency toward smaller ratios.

Because we did not observe any change in V distribution in either the regional deposition nor in the heterogeneity of the distribution, it is more likely that the observed widening and increased heterogeneity of the V/Q ratio distribution are

Table 3. Mean ± SD Regional Pulmonary Heterogeneity

	Consciousness State		
Variable	Awake	Anesthetized	*P* Value
SS_{total}	—	—	—
V	0.57 ± 0.15	0.48 ± 0.29	0.37
Q	0.37 ± 0.09	0.24 ± 0.14	0.002
V/Q	0.08 ± 0.02	0.13 ± 0.02	0.002
$SS_{vertical}$	—	—	—
V	0.16 ± 0.08	0.11 ± 0.07	0.15
Q	0.09 ± 0.04	0.06 ± 0.06	0.07
V/Q	0.008 ± 0.003	0.03 ± 0.03	0.03

Mild anesthesia (sevoflurane inhalation) with maintained spontaneous breathing was used. *P* values refer to awake *vs*. anesthetized state.

Q = perfusion; SS_{total} = global lung heterogeneity; $SS_{vertical}$ = vertical (ventral-to-dorsal) lung heterogeneity; V = ventilation.

the result of observed changes in Q between conditions. A feasible explanation is that Q is actively directed to follow the inherent natural inhomogeneities of V when awake and spontaneous breathing so that well-ventilated lung regions receive more blood flow whereas poorly ventilated areas receive less. However, during anesthesia, this regulatory mechanism is apparently affected so that the distribution of Q is less selective. This finding is reflected in the observed decrease in total variance of the Q regional distribution. As saturation remained within normal limits during anesthesia, this effect seems to be of limited importance in healthy volunteers. It may, however, be of greater importance among patients with compromised lung function.

A recent study[28] observed that mild hypoxia has no effect on the heterogeneity of Q, which makes it unlikely that pulmonary hypoxic vasoconstriction is actively affecting Q distribution under normal and mild hypoxic conditions. In addition, the influence from atelectasis formation during anesthesia was minimized during this study. Therefore, we hypothesized that the observed increase in V/Q heterogeneity during inhalation anesthesia was a direct effect of the inhaled anesthetic substance.

The limitations of our study deserve discussion. All findings in this work are based on the assumption that the radiotracer distributions observed accurately reflect V and Q distributions. Likewise, we assumed that the acquired images accurately represented tracer distribution. The deposition of both Technegas and LyoMAA has been shown to be proportional to the distribution of air and blood flow, respectively.[29–31] Phantom and physiologic studies using the same imaging technique and correction algorithms as demonstrated in this work have shown that corrected images are reliable estimates of the real distribution of radiotracers in the lungs.[26,27] Furthermore, anatomical positioning of the subjects during image registration was identical during anesthetized and awake states, and the time span between examination days was too short to be considered a confounding factor in these healthy volunteers. The SPECT scan corresponding to the anesthetized condition was always performed after reversing anesthesia and with the subject fully returned to consciousness to guarantee similar anatomy when compared to the awake condition. However, radiotracer distribution within the lungs at the time of the SPECT scan reflects the radiotracer distribution at the time of administration regardless of state. Therefore, our results are most likely caused by the anesthetic. Furthermore, no significant differences were observed between study groups by protocol sequence, i.e., awake-anesthetized *versus* anesthetized-awake.

Measurements of cardiac output required invasive procedures, a requirement that could have influenced pulmonary estimates of V and Q, our primary focus. However, pulse oximetry under anesthesia was performed (table 1).

Another limitation of our study is that respiratory parameters were not measured during awake administration of radiotracers. We have demonstrated, however, small differences in regional ventilation (tables 2 and 3). These data suggest that any difference in tidal volume or respiratory rate had little effect on ventilation distribution.

Observed high respiratory frequencies during inhalation anesthesia could influence measured end-tidal concentrations because of the limited response time of the Datex AS/3. This limitation could result in varying sevoflurane concentration values. Indeed, alveolar sevoflurane concentration values could be greater than in end-tidal samples.

In a recent study,[10] our group focused on the effect of posture on V, Q, and V/Q matching in healthy volunteers during mechanical ventilation. In that investigation, V distribution in the supine position was similar to that observed in the current study. However, results for Q distribution differed from those found in the current study by being more gravity dependent during mechanical ventilation. Although a balanced anesthetic technique was used in the previous study,[10] as compared to inhalation anesthesia in the current study, we believe that the major difference was mode of respiration, which may be an important factor for determining Q distribution. Indeed, mechanical ventilation through an endotracheal tube alters the anatomical dead space,[32] modifies total lung capacity, and bypasses the addition of nitric oxide in the paranasal sinuses.[33] Furthermore, mechanical ventilation induces positive airway pressure. Therefore, our results indicate that anesthesia with spontaneous breathing through a facial mask is more beneficial for V/Q matching. Inspiratory flow patterns differ between spontaneous breathing and mechanical ventilation, which may result in different regional ventilation, even with identical tidal volume. In addition, dead space will also be different between facial mask ventilation and endotracheal tube.

To our knowledge, no previous imaging study has been done on the distributions of V and Q during inhalation anesthesia in spontaneously breathing humans. Previous investigations have been made with awake or paralyzed and mechanically ventilated subjects.[14,34–36] A multiple inert gas–elimination technique study[17] done using spontaneously breathing subjects showed a widening V/Q distribution that was similar to that described for the current study.

In conclusion, we have shown evidence for increased regional V/Q heterogeneity during inhalation anesthesia and spontaneous breathing, which may contribute to a less effective pulmonary gas exchange. However, this impairment is less pronounced than that observed in anesthetized patients using mechanical ventilation in supine posture.[17]

The authors thank Anette Ebberyd, R.N., Technician, Department of Anesthesiology and Intensive Care, Karolinska University Hospital, Solna, Stockholm, Sweden, for her excellent help with the experiments.

References

1. Nunn's applied respiratory physiology, 6th ed. Edited by Lumb AB. Philadelphia, Elsevier/Butterworth-Heinemann, 2005, pp 310–5
2. Hlastala MP, Glenny RW: Vascular structure determines pulmonary blood flow distribution. News Physiol Sci 1999; 14:182–6

3. Beck KC, Rehder K: Differences in regional vascular conductances in isolated dog lungs. J Appl Physiol 1986; 61:530–8
4. Pelletier N, Robinson NE, Kaiser L, Derksen FJ: Regional differences in endothelial function in horse lungs: Possible role in blood flow distribution? J Appl Physiol 1998; 85: 537–42
5. West JB, Dollery CT, Naimark A: Distribution of blood flow in isolated lung; Relation to vascular and alveolar pressures. J Appl Physiol 1964; 19:713–24
6. Haas F, Bergofsky EH: Effect of pulmonary vasoconstriction on balance between alveolar ventilation and perfusion. J Appl Physiol 1968; 24:491–7
7. Rimeika D, Nyrén S, Wiklund NP, Koskela LR, Tørring A, Gustafsson LE, Larsson SA, Jacobsson H, Lindahl SG, Wiklund CU: Regulation of regional lung perfusion by nitric oxide. Am J Respir Crit Care Med 2004; 170:450–5
8. Jones AT, Hansell DM, Evans TW: Pulmonary perfusion in supine and prone positions: An electron-beam computed tomography study. J Appl Physiol 2001; 90:1342–8
9. Nyrén S, Mure M, Jacobsson H, Larsson SA, Lindahl SG: Pulmonary perfusion is more uniform in the prone than in the supine position: Scintigraphy in healthy humans. J Appl Physiol 1999; 86:1135–41
10. Nyrén S, Radell P, Lindahl SG, Mure M, Petersson J, Larsson SA, Jacobsson H, Sánchez-Crespo A: Lung ventilation and perfusion in prone and supine postures with reference to anesthetized and mechanically ventilated healthy volunteers. ANESTHESIOLOGY 2010; 112:682–7
11. Mure M, Nyrén S, Jacobsson H, Larsson SA, Lindahl SG: High continuous positive airway pressure level induces ventilation/perfusion mismatch in the prone position. Crit Care Med 2001; 29:959–64
12. Milic-Emili J, Henderson JA, Dolovich MB, Trop D, Kaneko K: Regional distribution of inspired gas in the lung. J Appl Physiol 1966; 21:749–59
13. Glenny RW: Determinants of regional ventilation and blood flow in the lung. Intensive Care Med 2009; 35: 1833–42
14. Tokics L, Hedenstierna G, Svensson L, Brismar B, Cederlund T, Lundquist H, Strandberg A: V/Q distribution and correlation to atelectasis in anesthetized paralyzed humans. J Appl Physiol 1996; 81:1822–33
15. Nunn JF, Bergman NA, Coleman AJ: Factors influencing the arterial oxygen tension during anaesthesia with artificial ventilation. Br J Anaesth 1965; 37:898–914
16. Hedenstierna G: Contribution of multiple inert gas elimination technique to pulmonary medicine. 6. Ventilation-perfusion relationships during anaesthesia. Thorax 1995; 50:85–91
17. Bindslev L, Hedenstierna G, Santesson J, Gottlieb I, Carvallhas A: Ventilation-perfusion distribution during inhalation anaesthesia. Effects of spontaneous breathing, mechanical ventilation and positive end-expiratory pressure. Acta Anaesthesiol Scand 1981; 25:360–71
18. Westbrook PR, Stubbs SE, Sessler AD, Rehder K, Hyatt RE: Effects of anesthesia and muscle paralysis on respiratory mechanics in normal man. J Appl Physiol 1973; 34:81–6
19. Hedenstierna G, Järnberg PO, Gottlieb I: Thoracic gas volume measured by body plethysmography during anesthesia and muscle paralysis: Description and validation of a method. ANESTHESIOLOGY 1981; 55:439–43
20. Takemura M, Shiokawa Y, Okamoto S, Uno H, Futagawa K, Koga Y: Volatile anesthetics constrict pulmonary artery in rabbit lung perfusion model. J Anesth 2005; 19:343–6
21. Marshall BE: Effects of anesthetics on pulmonary gas exchange, Anesthesia and the Lung. Edited by Stanley TH, Sperry RJ. London, Kluwer Academic Publishers, 1989, pp 117–25
22. Sykes MK, Loh L, Seed RF, Kafer ER, Chakrabarti MK: The effect of inhalational anaesthetics on hypoxic pulmonary vasoconstriction and pulmonary vascular resistance in the perfused lungs of the dog and cat. Br J Anaesth 1972; 44:776–88
23. Nunn's applied respiratory physiology, 6th ed. Edited by Lumb AB. Philadelphia, Elsevier/Butterworth-Heinemann, 2005, pp 297–326
24. Campbell EJ, Nunn JF, Peckett BW: A comparison of artificial ventilation and spontaneous respiration with particular reference to ventilation-bloodflow relationships. Br J Anaesth 1958; 30:166–75
25. Sinclair SE, Albert RK: Altering ventilation-perfusion relationships in ventilated patients with acute lung injury. Intensive Care Med 1997; 23:942–50
26. Sánchez-Crespo A, Petersson J, Nyren S, Mure M, Glenny RW, Thorell JO, Jacobsson H, Lindahl SG, Larsson SA: A novel quantitative dual-isotope method for simultaneous ventilation and perfusion lung SPET. Eur J Nucl Med Mol Imaging 2002; 29:863–75
27. Petersson J, Sánchez-Crespo A, Rohdin M, Montmerle S, Nyrén S, Jacobsson H, Larsson SA, Lindahl SG, Linnarsson D, Glenny RW, Mure M: Physiological evaluation of a new quantitative SPECT method measuring regional ventilation and perfusion. J Appl Physiol 2004; 96:1127–36
28. Arai TJ, Henderson AC, Dubowitz DJ, Levin DL, Friedman PJ, Buxton RB, Prisk GK, Hopkins SR: Hypoxic pulmonary vasoconstriction does not contribute to pulmonary blood flow heterogeneity in normoxia in normal supine humans. J Appl Physiol 2009; 106:1057–64
29. Amis TC, Crawford AB, Davison A, Engel LA: Distribution of inhaled 99mtechnetium labelled ultrafine carbon particle aerosol (Technegas) in human lungs. Eur Respir J 1990; 3:679–85
30. Taplin GV, MacDonald NS: Radiochemistry of macroaggregated albumin and newer lung scanning agents. Semin Nucl Med 1971; 1:132–52
31. Wagner HN Jr: Regional ventilation and perfusion, Principles of Nuclear Medicine. Edited by Wagner HN Jr., Szabo Z, Buchanan JW. Philadelphia, Saunders, 1995, pp 881–95
32. Casati A, Fanelli G, Torri G: Physiological dead space/tidal volume ratio during face mask, laryngeal mask, and cuffed oropharyngeal airway spontaneous ventilation. J Clin Anesth 1998; 10:652–5
33. Sánchez Crespo A, Hallberg J, Lundberg JO, Lindahl SG, Jacobsson H, Weitzberg E, Nyrén S: Nasal nitric oxide and regulation of human pulmonary blood flow in the upright position. J Appl Physiol 2010; 108:181–8
34. Rehder K, Knopp TJ, Sessler AD: Regional intrapulmonary gas distribution in awake and anesthetized-paralyzed prone man. J Appl Physiol 1978; 45:528–35
35. Lundh R, Hedenstierna G: Ventilation-perfusion relationships during halothane anaesthesia and mechanical ventilation. Effects of varying inspired oxygen concentration. Acta Anaesthesiol Scand 1984; 28:191–8
36. Anjou-Lindskog E, Broman L, Broman M, Holmgren A, Settergren G, Ohqvist G: Effects of intravenous anesthesia on VA/Q distribution: A study performed during ventilation with air and with 50% oxygen, supine and in the lateral position. ANESTHESIOLOGY 1985; 62:485–92