

Pulmonary Ventilation-Perfusion Relations after Heart Valve Replacement or Repair in Man *

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Decreased oxygenation of arterial blood has been recognized as a postoperative complication of major surgery since the report in 1943 by Maier and Cournand (1). Subsequent studies confirmed their finding by demonstrating low arterial oxygen saturation or tension, particularly after thoracic and cardiac surgery (2-6). These findings suggest increased physiologic shunting (or intrapulmonary venous admixture to arterial blood) as a cause for postoperative hypoxemia.

The use of extracorporeal circulation in cardiac surgery has led to such considerable problems of ventilation and oxygenation (5, 7-9) that specific lung damage is conjectured as a consequence of cardiopulmonary bypass (7, 8, 10).

The physiologic (or total) shunt is that part of the right heart output which does not participate in blood-gas exchange, but is returned unoxygenated to the left heart. The four causes recognized as contributing to the total shunt are the anatomical shunt, a diffusing gradient, uneven distribution of ventilation in relation to perfusion, and atelectasis (11).

The anatomical shunt through bronchial, pleural, and Thebesian veins constitutes approximately 2%¹ of cardiac output (13). A diffusing gradi-

ent is present at low alveolar oxygen tensions, but is considered negligible across normal alveolar membranes at alveolar oxygen tensions exceeding 100 mm Hg (14). Uneven distribution of ventilation in relation to perfusion contributes to shunting whenever alveoli are hypoventilated in relation to their perfusion (14). Atelectasis refers to air spaces that are not ventilated at all and, when perfused, cause shunting.

By the physiologic methods we use in this study it is impossible to distinguish between the venous admixture to arterial blood caused by the anatomical shunt and atelectasis. If, however, we accept *a*) that the anatomical component of the total physiologic shunt is, in the patients of this study, almost constant at 2% of the cardiac output and *b*) that diffusing gradients across normal alveolar membranes are negligible at alveolar oxygen tensions of above 100 mm Hg (14), we can make two conclusions about the components of the total physiologic shunt: 1) When 100% oxygen is inspired, the shunt caused by atelectasis is approximately equal to the total physiologic shunt minus 2% of the cardiac output (this assumes that denitrogenation of the patient has abolished the effect of uneven distribution). 2) The contribution of uneven distribution to the total physiologic shunt can be defined by the relatively simple technique of measuring the shunt, both when 100% oxygen and when room air is inspired.²

atomic shunt present in the patients of this study before surgery.

² These two conclusions each contain assumptions that require amplification. Our apparent dismissal of the effect of diffusing gradients is a matter of semantics. If, because of uneven distribution of ventilation in relation to perfusion, the oxygen tension of an alveolus is lowered sufficiently, then diffusing gradients may occur across that alveolar membrane. Primarily this is

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¹ The anatomical shunt may be larger than 2% in certain diseased states (12). An anatomic shunt of 2% of the cardiac output is our estimate of the average ana-

Uneven distribution of ventilation in relation to perfusion requires the presence in the hypoventilated alveoli of a "third" gas such as nitrogen in order to cause a significant alveolar-arterial oxygen gradient, or shunt. When 100% oxygen is inspired for a prolonged period, no such third gas is present; as long as any degree of ventilation of an air space persists, the oxygen tension in this air space can fall only as many millimeters of Hg as the carbon dioxide tension rises. Consequently, no significant shunt is caused by uneven distribution on 100% oxygen.

The purpose of this study was to determine the degree of physiologic shunting following open heart surgery, to identify the pulmonary pathophysiology causing this increased shunt, and to ascertain, if possible, whether a specific lesion can be recognized radiologically that may be considered a characteristic consequence of extracorporeal circulation.

Methods

Eighteen patients (Table I) were selected randomly from among those who underwent elective aortic or mitral valve surgery during a 6-month period. These 18 patients were divided into three groups: *a*) those who underwent aortic valve replacement (in one case debridement) and who at cardiac catheterization had no apparent mitral valve disease, *b*) those who underwent mitral valvuloplasty without extracorporeal circulation, and *c*) those who had mitral valve replacement or open valvuloplasty with the aid of extracorporeal circulation. (This group includes one patient who also had replacement of the aortic valve and tricuspid valvuloplasty.)

Fifteen of the eighteen patients had transeptal cardiac catheterization 1 to 4 weeks before operation. At catheterization and during studies 20 to 24 hours after surgery simultaneous samples of blood were obtained from the main pulmonary and right radial arteries, with the patient breathing room air. Immediately before or after arterial sampling, cardiac output was determined by analysis of dye dilution curves with a Gilford 103IR densitometer and a single injection of indocyanine green

"uneven distribution." In this paper we so classify it. If, even when 100% oxygen is inspired, a diffusing gradient is present because of extreme alveolar thickening, then the obliterated air space is functionally in a state of atelectasis. This form of shunting we classify as due to atelectasis. The shunt-like effect of diffusing gradients caused by thickened alveolar membranes should increase as the inspired oxygen tension is lowered. This increase in the effect of diffusing gradients with change from 100% oxygen to air is indistinguishable from "uneven distribution"; in this study both are arbitrarily called uneven distribution.

(amplification and recording were via a Sanborn 350 system). The dye was injected into the superior vena cava and arterial blood withdrawn from a peripheral artery; cardiac output was calculated from the recorded curve by the method of triangulation (15). In the preoperative studies cardiac output was also determined by the Fick principle, oxygen consumption being measured over 3 minutes by the open circuit method with a Beckman oxygen meter (model E 2). (No significant difference was found between Fick and dye techniques.) In the postoperative studies mixed venous blood was withdrawn through a pulmonary arterial catheter (no. 20 polyethylene). A second catheter of the same size was placed in the left atrium.

The techniques of surgery and extracorporeal perfusion followed principles outlined previously (16-19), except that direct coronary perfusion was provided in all patients who had replacement or correction of their aortic valve. Postoperatively, ventilation was not assisted apart from half hourly deep-breathing for 2 to 3 minutes by face mask and rebreathing bag. The temperature of each patient was monitored with a rectal electrode attached to a K-thermia blanket.³ For the period of the postoperative studies the rectal temperature was kept at $38^{\circ} \text{C} \pm 0.2^{\circ} \text{C}$.

Blood samples and dye dilution curves were first obtained with the patient inspiring room air. Subsequently 100% oxygen⁴ was given for a minimum of 20 minutes via a tight-fitting face mask and a nonbreathing system. (The tightness of the face mask was tested by spot checks of expired gas. For significance of possible errors in this method, see Table II.) Blood sampling and dye curves were then repeated. At the conclusion of the studies an X ray of the chest was taken. All blood samples were taken over at least three respiratory cycles. Expired gas and oxygen tanks were analyzed with a Beckman oxygen analyzer (model E 2) or by the Scholander micromethod (20). Patients were supine with a 15 degree head-up tilt.

In the postoperative studies arterial and pulmonary arterial blood was analyzed for oxygen tension, carbon dioxide tension, pH, oxygen content, and oxygen capacity ($P_{O_2} = 150$ mm Hg, temperature, 38°C). In the preoperative studies the only blood analyses made were for oxygen content and capacity.

Carbon dioxide tensions (P_{aCO_2} and $P\bar{V}CO_2$) were measured with the Severinghaus electrode (21), and pH was measured with a Radiometer microcapillary glass electrode. Oxygen tensions (P_{aO_2} and $P\bar{V}O_2$) were recorded with a modified Clark electrode⁵ (0.001-inch platinum cathode) (22) using a Sanborn polarization cell (model 350-416). Great care was taken to perform the polarographic measurements with the blood at 38°C within 3

³ Model R.K. 101, Gorman-Rupp Industries, Inc., Bellville, Ohio.

⁴ 100% oxygen when analyzed contained 0.2 to 0.5% impurities.

⁵ Beckman macroelectrode manufactured by Beckman Instruments Co., Fullerton, Calif.

TABLE I
Summary of individual data*

Patient no.	Age	Sex	Wt kg	Valve lesions	Preoperative C.I. L/min/m ²	Preoperative P.A. mm Hg	Operation	Extracorporeal perfusion time min	Postoperative radiological evidence of atelectasis	Other postoperative radiological pulmonary findings	Postoperative $\frac{\dot{Q}_s}{\dot{Q}} \times 100$ (room air)	Postoperative $\frac{\dot{Q}_s}{\dot{Q}} \times 0$ (O ₂)
1.†	63	M	74.5	A.S.	2.6	22	S.E.A.V.	153		Pleural effusion over right lower lung	13	8
2.	53	M	70.0	A.I.	1.3	11	A.D.	66			22	13
3.	71	F	61.4	A.S.	2.1	12	S.E.A.V.	86			14	15
4.	53	M	90.0	A.I.	1.7	11	S.E.A.V.	130			18	27
5.	50	M	69.5	A.S.	2.3	19	S.E.A.V.	127	++	Left lower lobe collapse	19	17
6.	57	M	69.1	A.S.	1.5	40	S.E.A.V.	60		Small right pleural effusion	12	12
7.	42	M	64.5	A.I.	2.6	12	S.E.A.V.	81			11	12
8.	56 ± 3.5	F	71.3 ± 3.5	A.S.	2.0 ± .20	18 ± 4.0		100 ± 14.2			15.5 ± 0.7	14.2 ± 1.7
9.	55	F	64.1	M.S.	2.8	18	2nd M.V.		+		25	16
10.	39	F	51.4	M.S.	2.0	35	2nd M.V.			Density, R.U.L.	13	12
11.	57	M	60.5	M.S.	1.8	32	1st M.V.		+	Fluid left pleural space	19	17
12.	64	F	51.4	M.S.	2.2 ± .3	28 ± 5.25	1st M.V.				6	7
13.	50 ± 3.5	F	57.1 ± 2.5	M.S.	2.2 ± .3	28 ± 5.25			+	Small left pleural effusion	13	7
14.	47	F	49.5	M.R.	1.3	45	S.E.M.V.	112		Patchy densities left lower lobe	35	17
15.	56	F	51.8	M.R.	2.6	25	S.E.M.V.	88	+		27	5
16.	48	M	76.8	M.S.	2.9	32	O.M.V.	50		Density left mid- and lower lung fields	15	10
17.	49	F	59.5	M.S.	1.5	30	O.M.V.	70	+	Small left pleural effusion	32	29
				T.S.			O.T.V.				19	7
				A.S.			O.A.V.					
18.	62	F	55.5	M.S.	1.8	58	O.M.V.	45			29	14
	54 ± 2.8		56.2 ± 4.6		2.0 ± .31	38 ± 6.0		78 ± 11.4			26.2 ± 1.7	13.7 ± 2.1

* Abbreviations: C.I. = cardiac index; P.A. = mean pulmonary arterial pressure; A.S. = valvular aortic stenosis; A.I. = aortic incompetence; M.S. = mitral stenosis; M.R. = mitral regurgitation; T.S. = tricuspid stenosis; S.E.A.V. = excision aortic valve and insertion prosthetic Starr-Edwards aortic valve; A.D. = debridement and commissurotomy of aortic valve; M.V. = mitral valvulotomy; S.E.M.V. = excision mitral valve and insertion prosthetic Starr-Edwards mitral valve; O.M.V. = open debridement of mitral valve and commissurotomy; O.T.V. = open debridement of tricuspid valve; O.A.V. = open debridement of aortic valve and commissurotomy; R.U.L. = right upper lobe.

† No. 1 died 21 days after aortic valve replacement. All other patients were discharged from the hospital.

TABLE II
Possible errors in measurements*

Source of error	Shunt estimated error (expressed as per cent of cardiac output) when inspiring		Reference
	Air	100% O ₂	
Laboratory error in O ₂ content determination†	±5%	±5%	23
Laboratory error in P _{O₂} or P _{CO₂} determination‡	<0.5%	<0.5%	21, 22, 25
A-aD for P _{CO₂} caused by shunt	-2%	<0.5%	26
Variation in expired and metabolic R from 0.85	±5%	<0.5%	27
Inaccuracy of 0.0031 as Bunsen solubility coefficient for O ₂ in W.B.	<0.5%	±2%	24, 25
Venous admixture from other than right heart	±0.8%	±0.8%	12
Inert gas in alveoli		< 3%	(There would be approximately a 3% error in calculation of shunt if 6% inert gas was present in the expired gas after 20 minutes of oxygen breathing.)
Inaccuracy or inapplicability of hemoglobin dissociation curve of Dill	-2%		28, 29, 30
The assumption of equal pH for arterial and alveolar equilibrated blood	-0.5%		30

The measurement of physiologic shunt expressed as per cent of the cardiac output Q ($Q_s/\dot{Q} \times 100$) thus carries a random error of ±5% of the cardiac output.

Source of error	Alveolar ventilation estimated error in % of \dot{V}_A	Reference
A-aD for P _{CO₂} caused by shunt	< 4-5%	26, 31
Calculation of \dot{V}_{O_2}	< ±20%	15
Assumption of R of 0.85	< ±30%	If R was 1.1 the error in calculation of \dot{V}_A is [(1.1-0.85)/0.85 × 100]% = 29%.

The measurements of \dot{V}_A and \dot{V}_{O_2} shown in Table III thus carry a random error of approximately ±30%.

* Abbreviations: P_{O₂} = oxygen tension; P_{CO₂} = carbon dioxide tension; A-aD = alveolar-arterial O₂ difference; R = respiratory quotient; W.B. = whole blood; \dot{V}_{O_2} = oxygen consumption.

† Mean error of duplicate analyses: 0.12 vol per 100 ml, SD ± 0.17.

‡ Mean error of duplicate analyses: 1.8%, SD ± 1.2%. Mean error of individual measurement with tonometered blood or water: 1.9%, SD ± 1.6%.

minutes from sampling. The accuracy of Severinghaus and Clark electrodes was repeatedly checked against water or blood equilibrated with known percentages of oxygen and carbon dioxide. For P_{O₂} and P_{CO₂} the reproducibility of any particular sample was found to be within 2%. The oxygen contents of the pulmonary artery ($C\dot{V}_{O_2}$) and arterial blood (Ca_{O_2}) were determined by the method of Van Slyke and Neill (23). All measurements were required to check to within ±0.2 vol per 100 ml for any particular sample. Oxygen capacity at P_{O₂} = 150 mm Hg, temperature, 38° C (Cap), was determined by equilibrating the blood at 38° C with a known oxygen tension in excess of 140 mm Hg and then measuring the blood oxygen content. Correction for discrepancy in dissolved oxygen was made by subtracting or adding the multiple of 0.0031 times the amount the tension differed from 150 [0.0031 is the Bunsen coefficient for the amount of oxygen physically dissolved in

blood (volume per 100 ml) under a pressure gradient of 1 mm Hg at 38° C] (24, 25). After tonometry the oxygen tension of the blood always agreed to within 2% of the oxygen tension of the equilibrating gas. The technique of tonometry used to determine the oxygen capacity has been previously described by Hedley-Whyte and Laver (25).

The X rays of the chest taken at the conclusion of the studies were examined independently by two radiologists.

The statistical methods and the equations used to calculate ideal alveolar oxygen tension (P_{aO₂}), total physiologic shunt ($\dot{Q}_s/\dot{Q} \times 100$), oxygen consumption (\dot{V}_{O_2}), and alveolar ventilation (\dot{V}_A) are shown in the Appendix.

Table II shows the source of possible errors in this study and gives our own and previous workers' (12, 15, 21-31) estimates of the significance of these errors.

We submit that the majority of the errors cited in Table II operate randomly, and we therefore believe that

TABLE III
Effect of 100% O₂ and room air 20 to 24 hours after surgery (mean values ± SE)*

	PAO ₂	PaO ₂	Paco ₂	pH	CaO ₂	C \bar{v} O ₂	C.I.	\dot{V} O ₂	\dot{V} A	L.A. mean
	mm Hg	mm Hg	mm Hg		ml/100 ml W.B.	ml/100 ml W.B.	L/min/m ²	ml/min/m ²	L/min/m ²	mm Hg
Open aortic	101 ± 2.1	65 ± 3.9	42 ± 1.2	7.39 ± 0.04	17.2 ± 0.8	11.4 ± 0.6	2.8 ± 0.4	156 ± 18	2.7 ± 0.3	9.9 ± 1.5
	669 ± 4.8	319 ± 43.9	42 ± 3.2	7.40 ± 0.02	19.2 ± 0.8	12.0 ± 0.7	2.7 ± 0.5	177 ± 22	3.6 ± 0.6	10.6 ± 1.9
Closed mitral	104 ± 2.5	67 ± 3.6	39 ± 2.4	7.44 ± 0.03	15.9 ± 1.0	9.7 ± 0.9	2.0 ± 0.3	130 ± 36	2.5 ± 0.8	9.6 ± 0.3
	671 ± 65.0	356 ± 65.0	41 ± 3.1	7.41 ± 0.02	18.0 ± 1.0	9.7 ± 1.1	2.2 ± 0.4	169 ± 63	3.6 ± 1.4	8.8 ± 0.6
Open mitral	104 ± 2.4	53 ± 3.1	40 ± 2.3	7.44 ± 0.01	16.4 ± 1.3	9.2 ± 0.6	2.0 ± 0.2	151 ± 12	2.8 ± 0.3	9.0 ± 2.2
	669 ± 2.6	324 ± 54.4	44 ± 2.0	7.41 ± 0.01	19.8 ± 1.3	11.5 ± 0.7	2.0 ± 0.4	145 ± 25	2.8 ± 0.5	10.5 ± 2.3

* Abbreviations: PAO₂ = alveolar oxygen tension; PaO₂ = arterial oxygen tension; Paco₂ = carbon dioxide arterial tension; CaO₂ = oxygen content of arterial blood; C \bar{v} O₂ = oxygen content of the pulmonary artery; C.I. = cardiac index; \dot{V} O₂ = oxygen consumption; \dot{V} A = alveolar ventilation; L.A. = left atrial pressure.

any individual measurement of shunt had a random error of less than ±5% of the cardiac output. This degree of accuracy is sufficient for the purposes of this study but would not be sufficient for the study of physiologic shunting in normal man.

Our technique for measuring alveolar ventilation (\dot{V} A) and oxygen consumption (\dot{V} O₂) is subject to random errors of ±30%. These parameters are included in Table III only to show that increased physiologic shunting was not caused by alveolar hypoventilation or by changes in \dot{V} O₂.

Results

Decreased oxygenation and large physiologic shunts were found in all patients, when studied 20 to 24 hours after cardiac surgery. The degree of impaired oxygenation was such that arterial oxygen tensions were in the hypoxic range. When the patients were allowed to breathe room air after closed mitral valvulotomy, mean PaO₂ was 67

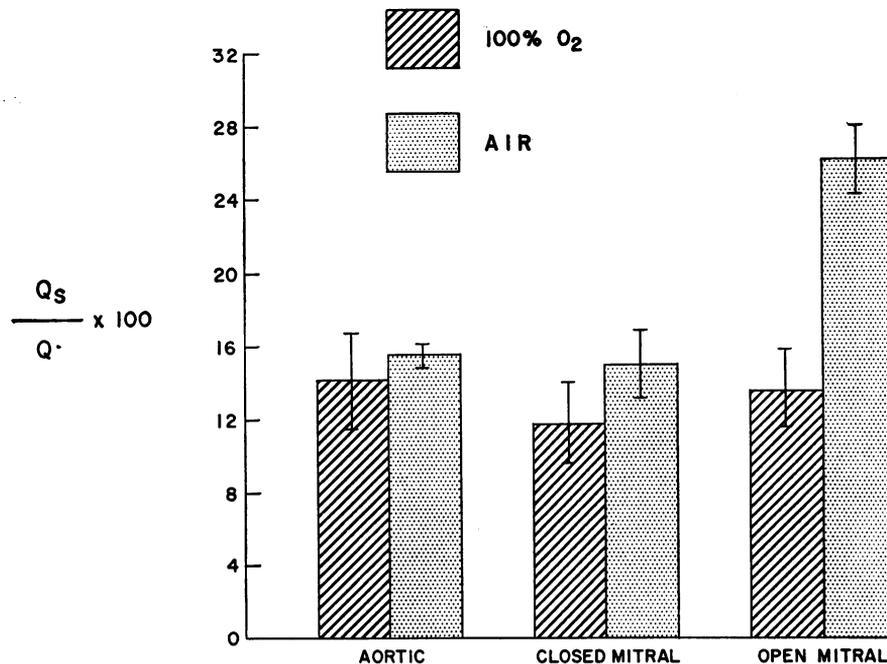


FIG. 1. MEAN VALUES (± SE) FOR PHYSIOLOGIC SHUNT (PULMONARY VENOUS ADMIXTURE) 20 TO 24 HOURS AFTER AORTIC VALVE REPLACEMENT, CLOSED MITRAL VALVULOTOMY, OR OPEN MITRAL VALVE REPLACEMENT OR REPAIR. Values for shunt breathing 100% O₂ are compared with the shunt breathing air. The shunt breathing air is significantly greater ($p < 0.01$) than the shunt breathing 100% O₂ in the patients who have had open mitral valve replacement or repair.

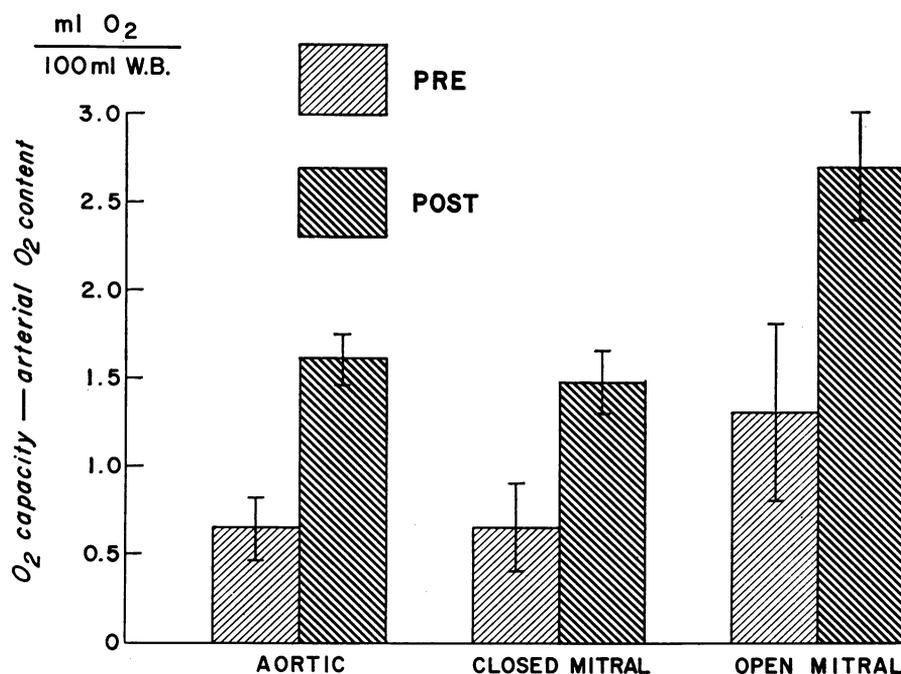


FIG. 2. MEAN VALUES (\pm SE) FOR O₂ CAPACITY MINUS ARTERIAL O₂ CONTENT (ML O₂ PER 100 ML WHOLE BLOOD) WHEN BREATHING AIR. Preoperative values were obtained at cardiac catheterization 1 to 4 weeks before aortic valve replacement, closed mitral valvulotomy, or open mitral valve replacement or repair. Postoperative values were obtained 20 to 24 hours after surgery and are significantly greater than the differences between O₂ capacity and arterial O₂ content found before operation ($p < 0.01$ for the aortic, $p < 0.1$ for the closed mitral, and $p < 0.05$ for the open mitral patients).

mm Hg; after open aortic valve replacement mean Pa_{O₂} was 65 mm Hg, and after open mitral surgery mean Pa_{O₂} was only 53 mm Hg (Table III).

The postoperative shunts were measured both on 100% oxygen and on room air. On 100% oxygen the average shunts were 12, 14, and 14% of cardiac output after closed mitral, open aortic, and open mitral valve surgery, respectively. On room air the corresponding values were 15, 15, and 26% of cardiac output (Figure 1 and Table I). Thus the shunt was invariably larger on room air, but only after open mitral surgery did the difference reach proportions that are statistically significant ($p < 0.01$). The postoperative shunts on 100% oxygen and on room air are shown graphically in Figure 1. The contribution of uneven distribution to shunting can be obtained from the values shown in Figure 1 by subtracting the shunt on 100% oxygen from the shunt on room air.

Impairment of oxygenation was markedly increased by surgery (Figure 2). For comparison

of postoperative with preoperative values the impaired oxygenation is expressed as oxygen capacity (in vol per 100 ml at Po₂ of 150 mm Hg) minus arterial oxygen content. It is apparent that this difference between oxygen capacity and arterial oxygen content was more than doubled in all three groups; increases were significant at a level of $p < 0.01$ after aortic surgery, $p < 0.05$ after closed mitral surgery, and $p < 0.1$, > 0.05 after open mitral surgery. The patients having open mitral surgery had the largest preoperative impairment of oxygenation. This postoperative increase in the difference between oxygen capacity and arterial oxygen content was not caused by an increased oxygen carrying capacity of the blood since the over-all average oxygen capacity was 19.3 vol per 100 ml before operation and 19.0 vol per 100 ml 24 hours after surgery.

In an attempt to determine a possible causal relationship, the postoperative increase in the difference between oxygen capacity and arterial oxy-

gen content was tested for correlation with the following variables, none of which was significant at the 5% level: hypoventilation (Table III), changes in cardiac output (Tables I and III), radiological evidence of atelectasis (Table I), anemia (Table III), pulmonary arterial hypertension (Figure 3), or left atrial hypertension (Table III). Oxygen consumption increased an average of 20% after operation, consistent with an observed average increase in oral temperature of 1.2° C. Figure 4 shows the abnormally large arteriovenous O₂ differences found in many of the patients.

Hypoventilation was not present at the time of the postoperative study, as shown by PaCO₂ values in Table III. The highest postoperative PaCO₂ value was 52 mm Hg, obtained in a 71-year-old patient breathing room air after open aortic surgery. Acid-base balance was almost normal, with little evidence of either respiratory or metabolic acidosis. The lowest pH at the time of study was 7.32, and this modest acidosis was metabolic rather than respiratory in nature. Detailed tables of the following parameters: PaO₂, PaCO₂, pH, CaO₂, C \bar{v} O₂, cardiac index (C.I.), mean pulmonary arterial pressure (P.A.), left atrial pressure (L.A.), and oxygen consumption

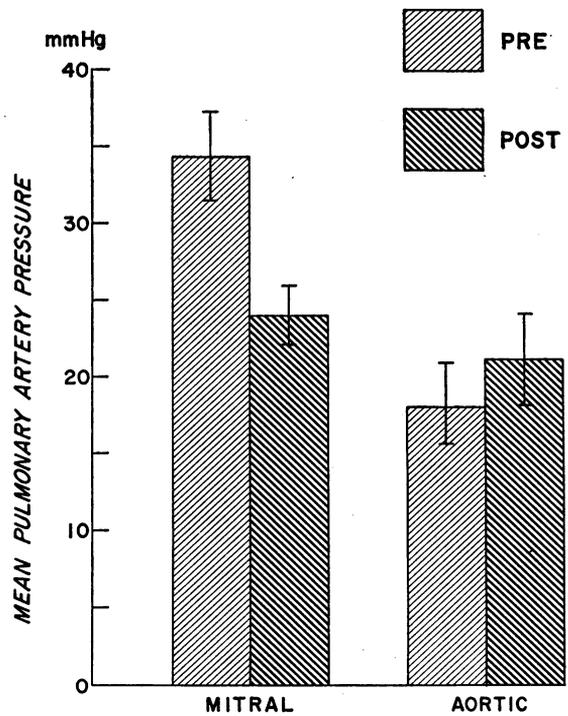


FIG. 3. MEAN VALUES (\pm SE) FOR PULMONARY ARTERIAL PRESSURE 1 TO 4 WEEKS BEFORE AND 20 TO 24 HOURS AFTER PROSTHETIC REPLACEMENT OF THE AORTIC OR MITRAL VALVE. The decrease in pulmonary arterial pressure was significant ($p < 0.01$) after mitral valve replacement or repair.

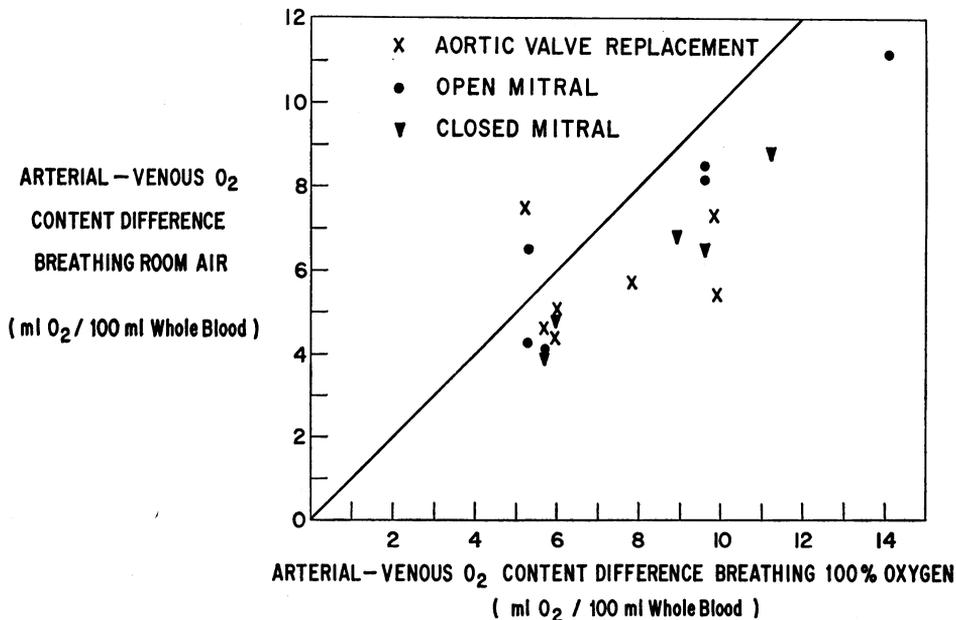


FIG. 4. THE ARTERIOVENOUS OXYGEN CONTENT DIFFERENCE (A-V_{O₂}) OF EACH PATIENT BREATHING AIR PLOTTED AGAINST THE A-V_{O₂} DIFFERENCE WHEN BREATHING 100% OXYGEN.

(\dot{V}_{O_2}) have been deposited⁶ and are available on request.

One patient in this study died (Patient 1, Table I). Death occurred 21 days after these studies, and autopsy confirmed the clinical diagnosis of acute tubular necrosis.

Discussion

After cardiac surgery arterial oxygen tension fell to hypoxic levels when room air was inspired. The cause of this increased hypoxemia was physiologic shunting. These large shunts were also present while the patients were breathing 100% oxygen, and thus we conclude that the most important single cause of postoperative shunting in these patients was atelectasis. This lesion is defined in pathophysiological terms as a state of continued perfusion of alveoli that receive no ventilation at all.

These perfused but unventilated alveoli were probably widely scattered, and essentially no agreement was found between atelectasis as here defined and conventional radiological evidence of atelectasis (Table I).

There was no significant difference in the magnitude of shunts in the three groups studied, regardless of whether extracorporeal circulation was used or not. This finding is compatible with other reports that indicate that hypoxemia is generally present after all major surgery (1-6). Only McClenahan, Sykes, and Young (9) have suggested that hypoxemia and large shunts are a unique consequence of open heart surgery.

The increase in shunting on room air, as compared with 100% oxygen, was modest except in the patient group that had open mitral surgery. This increase in shunting may be explained on the basis of uneven distribution of ventilation in relation to perfusion; as the "third" gas, nitrogen, becomes available, an additional shunt effect is caused by alveoli that are hypoventilated in relation to their perfusion. If the distribution of ven-

tilation is sufficiently uneven, one must assume that a diffusing gradient adds to the shunt, because in the least ventilated alveoli the oxygen tension may be sufficiently low, or the alveolar membranes sufficiently thickened, to establish a diffusing block.

The addition of the distribution effect is not the only possible cause of increased shunting on room air. The shunt equation (see Appendix) makes it evident that, with the numerator (i.e., the A-a O_2 gradient) constant, any decrease in the denominator (i.e., the A- \bar{v} O_2 gradient) will result in a higher numerical value of the shunt. Figure 4 demonstrates that the A- \bar{v} O_2 gradients were consistently lower (approximately 20 to 25%), as expected, on room air than on 100% oxygen. Therefore, the larger shunts on room air are explainable, in part, on the basis of a fall in A- \bar{v} O_2 gradients. A redistribution of pulmonary blood flow is a further possibility: in order to explain an increase in shunt on this basis one would have to assume a redistribution favoring the "shunt-producing" gas exchange units. Although not likely to account for the entire change, this can neither be proved nor disproved.

Patients with mitral stenosis are known to have parenchymal lung changes that may cause significant uneven distribution of ventilation in relation to perfusion (32). In our present study, however, only in the group who had mitral valve replacement or open repair was the shunt so much larger on room air than on 100% oxygen that the uneven distribution effect became a major component of the shunt. In this group the shunt doubled on room air, and so large an increase is clearly not explicable on the basis of change in the A- \bar{v} O_2 gradient. The degree of shunting, moreover, bore no relation to the degrees of postoperative pulmonary hypertension.

By the techniques used in this study we cannot prove or disprove a marked postoperative increase in that portion of the bronchial arterial flow that drains into the left atrium. However, the magnitude of the postoperative impairment of oxygenation found in every patient makes it unlikely that these channels (12) are a major source of postoperative shunting. Likewise it seems difficult to conceive that other sources of the normal anatomical shunt, such as the Thebesian vessels, can contribute significantly to the observed large increases in the total physiologic shunt.

⁶ Detailed tables of these nine parameters have been deposited as document number 8235 with the American Documentation Institute Auxiliary Publications Project, Photoduplication Service, Library of Congress, Washington, D. C. 20540. A copy may be secured by citing the document number and remitting \$1.25 for photoprints or 35 mm microfilm. Advance payment is required. Make checks or money orders payable to: Chief, Photoduplication Service, Library of Congress.

We suggest therefore that atelectasis with significant shunting is the common denominator in causing postoperative impairment of oxygenation. Similar studies done during operation (unpublished data) have revealed that shunting of similar magnitude is present at this time and that the shunt before the period of extracorporeal circulation is just as large as the shunt after perfusion, the pattern of ventilation being identical. The oxygenation impairment cannot, therefore, be related to any specific pulmonary damage inflicted during the period of perfusion. Instead, the atelectasis and shunting found postoperatively in these studies must be explained as insufficient re-expansion of the lungs during and after the period of open chest surgery and also on the basis of an unfavorable pattern of ventilation.

In previous studies (33-36) we have found the pattern of ventilation to be the single most important factor in determining the degree of atelectasis and shunting; a pattern of fast and shallow breathing promotes atelectasis and shunting, whereas large tidal volumes prevent this complication (34). Periodic deep breathing with very large tidal volumes is effective in reversing atelectasis and shunting of relatively short duration (33, 36). The most important causes of shallow breathing, lacking in spontaneous, periodic deep breaths, are pain and morphine given for relief of pain (37).

Thus, we have found the major pulmonary complication of cardiac surgery to be deficient oxygenation rather than hypoventilation. Accordingly, we do not use mechanical respiratory support routinely, only on specific indications. Instead, the postoperative regimen calls for careful monitoring of arterial and venous blood gases, for the use of sufficient inspired oxygen to produce an arterial oxygen tension of 100 mm Hg, for intensive chest physiotherapy with coughing and deep breathing exercises, and for passive deep breathing every 30 minutes around the clock.

Summary

Large physiologic shunts causing hypoxemia were found in all patients on air 20 to 24 hours after cardiac surgery. The average physiologic shunt on 100% oxygen was 13% of cardiac output, and it was concluded that the most important single cause of these shunts was diffuse atelectasis, usu-

ally invisible to X ray. Extracorporeal circulation had no apparent effect in increasing physiologic shunting. However, the increase in shunting on room air, as compared with oxygen, was significant in the group of patients who had mitral valve replacement or open mitral valvuloplasty ($p < 0.01$). This increase, caused by uneven distribution of ventilation in relation to perfusion, was equivalent to a right to left shunt of 12.5% of the cardiac output. The combination of atelectasis and maldistribution resulted in the mean arterial oxygen tension on air of this group being only 53 mm Hg.

Appendix

Calculations. Mean alveolar oxygen tension, PA_{O_2} , was calculated from the alveolar gas equation (26) by arbitrarily assuming an RQ of 0.85 when air was inspired.

To derive the per cent of the cardiac output that did not become fully oxygenated on its passage through the pulmonary circulation (total shunt, $\dot{Q}_s/\dot{Q} \times 100$) the following equation was used (38):

$$\frac{\dot{Q}_s}{\dot{Q}} = \frac{Cc'_{O_2} - Ca_{O_2}}{Cc'_{O_2} - C\bar{v}_{O_2}} \quad [1]$$

where Ca_{O_2} = oxygen content of arterial blood, $C\bar{v}_{O_2}$ = oxygen content of mixed venous blood, and Cc'_{O_2} = the oxygen content that the patient's arterial blood would have had if equilibrated with mean alveolar gas.

Two equations were used to calculate Cc'_{O_2} when 100% oxygen was inspired:

a) When PA_{O_2} was greater than 150 mm Hg, advantage was taken of the fact that at these high oxygen tensions hemoglobin is effectively fully saturated. Thus, the difference between Ca_{O_2} and Cc'_{O_2} was determined by multiplying the corresponding oxygen tension difference by the Bunsen solubility coefficient for oxygen in blood (0.0031 vol per 100 ml per mm Hg) (24, 25).

$$Cc'_{O_2} = Ca_{O_2} + (PA_{O_2} - Pa_{O_2}) \times 0.0031. \quad [2]$$

b) When PA_{O_2} was less than 150 mm Hg, the oxygen capacity of the blood at $PO_2 = 150$ mm Hg, temperature, 38° C (Cap), was determined in a tonometer (25). Above PO_2 150 mm Hg hemoglobin is effectively fully saturated, and thus the difference between Cc'_{O_2} and Cap can be expressed, as in Equation 2, by multiplying the tension difference by the Bunsen solubility coefficient for oxygen in whole blood.

$$Cc'_{O_2} = Cap + (PA_{O_2} - 150) \times 0.0031. \quad [3]$$

The calculation of Cc'_{O_2} when room air was inspired was done in two stages. First, the tables of Dill (30) were read to find the saturation that blood would have if equilibrated with mean alveolar air (Sc'_{O_2}) (the pH of this blood was assumed to be the patient's arterial pH). Second, the standard formula,

$$\text{percentage saturation} = \frac{(\text{O}_2 \text{ content-dissolved O}_2)}{\text{O}_2 \text{ capacity-dissolved O}_2} \times 100,$$

was solved for O₂ content:

$$Cc'_{\text{O}_2} = Sc'_{\text{O}_2} \times (\text{Cap} - 0.0031 \times 150) + (\text{PA}_{\text{O}_2} \times 0.0031). \quad [4]$$

Oxygen consumption, milliliters O₂ per square meter per minute (\dot{V}_{O_2}), was calculated from the cardiac index and the arteriovenous oxygen content difference (a-v O₂) (31).

$$\dot{V}_{\text{O}_2} = 10 \text{ C.I.} \times \text{a-v O}_2, \quad [5]$$

where C.I. is the cardiac index in liters per square meter per minute.

Alveolar ventilation (\dot{V}_A), liters per minute, was calculated from the following equation (31):

$$\dot{V}_A = \frac{0.863 \cdot \dot{V}_{\text{O}_2} \cdot R}{\text{Paco}_2}, \quad [6]$$

where R is the respiratory quotient (arbitrarily assumed to be 0.85).

Statistical testing of the effect of operation and of breathing 100% oxygen was by the *t* test, using the method of paired comparison (39).

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