Effect of Percutaneous Transcatheter Embolization on Pulmonary Function, Right-to-Left Shunt, and Arterial Oxygenation in Patients with Pulmonary Arteriovenous Malformations[1,2]

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SUMMARY The effects of percutaneous transcatheter embolization on pulmonary function and exercise capacity were assessed in 15 patients with pulmonary arteriovenous malformations (PAVM). Vital capacity (VC), FEV_1, DL_{CO}, Sa_{O_2}, exercise performance, and right-to-left shunt (100% oxygen method) were measured before and 2 to 6 months after treatment. Surgical correction had been attempted in 9 patients prior to referral, and 11 had associated hereditary hemorrhagic telangiectasia (HHT). Lung function tests before intervention showed normal VC and FEV_1/VC ratios, reduced DL_{CO} (mean 71% predicted, range 36 to 123%), a resting supine Sa_{O_2} of 86% (range 67 to 95%) and mean shunt fraction of 33% (range 15 to 47%). Despite further marked falls in Sa_{O_2} on exertion, exercise capacity was well preserved. Following steel coil embolization of all PAVM with a feed vessel internal diameter > 3 mm (one to four sessions per patient), mean shunt fraction improved from 33 to 19% and resting Sa_{O_2} from 86 to 92% with no change in VC. A consistent improvement in diffusing capacity was seen only in patients with coexisting HHT. Exercise capacity increased in the majority (unchanged in 6), and Sa_{O_2} during maximal exercise improved in all except one patient. There were no long-term complications following embolization. These findings indicate that embolization of all macroscopic PAVM, undertaken primarily to reduce the risk of paradoxical embolization, is safe and results in substantial improvements in resting and exercise Sa_{O_2} without evidence of loss of normal lung. The right-to-left shunts remaining following embolization may reflect the presence of numerous microscopic PAVM in these patients.

AM REV RESPIR DIS 1990; 142:420-425

Introduction

Pulmonary arteriovenous malformations (PAVM) comprise abnormal vascular channels connecting the pulmonary artery and pulmonary vein and give rise to a right-to-left shunt and arterial hypoxemia (1, 2). They are usually embedded within the lung parenchyma and can vary in size between a large aneurysmal lesion and the microscopic vessels characteristic of patients with associated hereditary hemorrhagic telangiectasia (HHT) (2, 3). Although most PAVM are thought to be congenital, the classic features of cyanosis, clubbing, and overlying bruit are usually not evident until adult life (2, 4) as most appear to enlarge gradually throughout childhood.

The recognition of the high morbidity and mortality associated with PAVM, due mainly to paradoxical emboli passing into the systemic circulation (1, 5, 6), and the recent development of transcatheter embolization techniques (3, 7–10) have resulted in early intervention being recommended for the majority of patients (2, 11). The safety of transcatheter embolization and the ability to ablate multiple lesions without sacrificing normal lung have made this approach the treatment of choice in most cases (2).

Clinically, the disparity between the symptoms and signs in patients with PAVM is often striking, with breathlessness a relatively late or mild feature even in the presence of a large right-to-left shunt. In addition, a number of patients with major shunts and marked cyanosis have a normal or near normal ability to exercise and some remain asymptomatic throughout adult life. This discrepancy between the often marked arterial desaturation and near normal exercise capacity has not been previously examined. In addition, although the cardiovascular and hematologic consequences of PAVM have been well documented (12–14), pulmonary gas exchange, exercise capacity, and the relationship of these parameters to shunt size have not been studied in detail, and apart from changes in Pa_{O_2} (9), the consequences of percutaneous embolization on lung function and shunt size have likewise not been reported.

We have performed pulmonary function testing, including measurement of gas exchange, exercise capacity, and shunt fraction, in 15 patients with PAVM and assessed the effect on these parameters of embolizing all large PAVM. The definitive physiologic measurement, that of right-to-left shunt, has not been emphasized in the previous literature, nor has the increase in hypoxemia on exercise been commented on.

Methods

Subjects Studied

A total of 15 patients, aged 13 to 63 yr, was assessed. The clinical features at presentation are detailed in table 1. All had angiographically proven PAVM that were multiple in 13 patients and involved both lungs in 10. Clinical evidence of HHT was seen in 11 patients. Liver function tests were normal in all subjects and none had clinical evidence of cirrhosis. All were lifelong nonsmokers except one (Subject 13). Thoracotomy, with attempted surgical ligation or resection of lobes with single large PAVM, had been undertaken prior to referral in eight of the 15 patients. An additional five patients with PAVM were as-

(Received in original form August 28, 1989 and in revised form January 22, 1990)

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TABLE 1

CLINICAL DETAILS AT PRESENTATION

Subject Details	Age	Sex	HHT	Presentation	Clubbing	PAVM Location	Previous Lobectomy	Hb (g/dl)
1 AC	27	F	+	Dyspnea, TIA	+	Widespread	*	18.4
2 SC	56	F	+	Septic emboli	–	LLL	–	8.1
3 FH	56	F	+	None	–	RML, LLL	RLL	11.3
4 AH	24	M	+	Headache	+	Widespread	–	19.1
5 FK	48	F	+	Dyspnea	–	LLL	–	13.4
6 IL	63	F	+	None	+	LLL, RLL	–	18.1
7 LM	29	F	+	Dyspnea	+	Widespread	LLL	13.9
8 MR	46	F	+	Stroke	–	Widespread	Ligation	12.9
9 AW	55	M	+	None	–	RLL	LLL + lingular	15.9
10 BW	39	M	+	Dyspnea	+	Widespread	Ligation	17.6
11 SP	13	F	+	Dyspnea	+	Widespread	–	18.1
12 PD	35	M	–	Dyspnea	+	Widespread	LUL	21.6
13 MH	36	M	–	Dyspnea, TIA	+	LLL	LUL	17.3
14 RH	40	M	–	Dyspnea	–	LLL, RLL, RUL	*	16.8
15 BW	50	M	–	TIA	+	RLL	–	15.7

Definition of abbreviations: HHT = hereditary hemorrhagic telangiectasia; TIA = transient ischemic attack.
* Previous thoracotomy, no ligation or resection performed.

sessed over the period of this study in whom embolization was not performed. Two of these patients had intrapulmonary shunting secondary to underlying chronic liver disease, one had exclusively microvascular shunt vessels, and two patients who were asymptomatic declined intervention.

FEV_1, VC, D_{LCO}, Sa_{O_2}, right-to-left shunt fraction and exercise performance were measured in all patients prior to embolization. Follow-up assessments were performed between 2 and 6 (mean 4.1) months following embolization.

Lung Function Tests

FEV_1 and VC were measured using a dry wedge spirometer (Vitalograph, Buckingham), recording the best of three attempts. Single-breath carbon monoxide transfer factor (D_{LCO}) was measured by the method of Ogilvie and coworkers (15). The percentage of predicted values was derived for spirometry from normal ranges from Quanjer (16) and for the transfer factor from Bradley and colleagues (17). The D_{LCO} and transfer coefficient Kco (D_{LCO}/V_A) were corrected to a standard hemoglobin concentration of 14.6 g/dl. Arterial oxygen saturation was measured supine using an Ohmeda Biox 3700 pulse oximeter (18).

Exercise Tests

Incremental exercise testing was performed in the erect posture using a cycle ergometer with increases in work load at the end of each minute, continuing until symptom-limited maximal exertion was reached. Work load was increased by 15 or 30 W at each stage depending on exercise capacity. Using a visual analog scale (19), patients scored breathlessness, tiredness, and effort perception before and after exercise and usually recorded maximal effort prior to stopping. Heart rate (ECG monitor) and Sa_{O_2} were recorded at the end of each minute.

Measurement of Right-to-Left Shunt

The anatomic shunt was measured supine with patients breathing 100% oxygen from a Douglas bag for 15 min. A mouthpiece, two-way valve, and noseclip were used to ensure delivery of 100% oxygen, and a deep breath was taken every minute. An arterial blood gas sample was then taken and analyzed immediately for Pa_{O_2}. Using the Sa_{O_2} (measured independently using the oximeter) and Pa_{O_2} values on 100% oxygen and current hemoglobin concentration, the shunt fraction was calculated from the classic equation (20) as follows:

$$\frac{\dot{Q}s}{\dot{Q}T} = \frac{Ci_{O_2} - Ca_{O_2}}{Ci_{O_2} - C\bar{v}_{O_2}}$$

where

$\dot{Q}s/\dot{Q}T$ = shunt as a fraction of total flow

Ci_{O_2} = oxygen content of "ideal" (non-shunt) blood (ml/100 ml) (0.003 × 650) + (1.39 × Hb g/dl × 100/100)

Ca_{O_2} = oxygen content of arterial blood (ml/100 ml) (0.003 × Pa_{O_2} mm Hg) + (1.39 × Hb g/dl × Sa_{O_2}/100 ml)

$C\bar{v}_{O_2}$ = oxygen content of mixed venous blood (ml/100 ml) (Ca_{O_2} − 5)

This calculation assumes a physical solubility of oxygen in blood of 0.003 ml/100 ml/mm Hg, a blood oxygen content equal to dissolved O_2 and HbO_2, an effective alveolar Pa_{O_2} on 100% oxygen of 650 mm Hg, and an arteriovenous oxygen content difference of 5 ml/100 ml blood.
respectively).

PAVM Embolization

Percutaneous transcatheter embolization of all PAVM was performed under local anesthesia using steel coils as described previously (10, 11) and as illustrated in figure 1. The primary intent of embolization was to ablate all angiographically significant shunt vessels to reduce the risk of paradoxical embolization, and therefore all shunts with feeding vessels with an internal diameter > 3 mm were embolized. This was usually achieved in one or two sessions, separated by an interval of 2 to 6 months, although in patients 4, 12, and 13 up to four embolization procedures were required to occlude completely all large PAVM. In four patients (Subjects 1, 6, 10, and 11), residual macroscopic PAVM remain after the initial embolizations, and further procedures are planned. The only complications relating to the angiography and embolization procedures were a femoral vein thrombosis in a patient with severe polycythemia and a single pulmonary infarct in another subject due to placing a coil proximal to a feeding vessel, resulting in occlusion of the arterial supply to normal lung. Both resolved fully.

Statistical Analysis

Pre- and postembolization values for VC, shunt fraction, Kco, and Sa_{O_2} were compared using a paired *t* test. Linear regression analysis and quadratic regression analysis were used to correlate preembolization hemoglobin and pulmonary function values (see RESULTS).

Results

The clinical characteristics of our patients with PAVM are typical of those reported elsewhere (1, 12). The majority of lesions were situated in the lower lobes, and with careful digital subtraction angiography multiple PAVM were identified in all except two patients. Prior to embolization, five patients were polycythemic. The 11 patients with HHT had a slightly lower mean hemoglobin concentration of 15.2 ± 1.1 g/dl (mean ± SEM) compared to 17.9 ± 1.3 g/dl in those without clinically evident telangiectasia. There was no correlation between hemoglobin concentration and Sa_{O_2} or shunt fraction (r = 0.271 and 0.443, respectively).

Pulmonary Function Tests

Preembolization pulmonary function, arterial saturation, and shunt data are shown in table 2. The vital capacity was greater than 70% predicted normal in all except one patient (who had had a previous lung resection), with a mean percentage predicted value of 85 ± 4% for all patients and 87 ± 4% excluding those with a history of lobectomy. Excluding Patients 9 and 13, who had coexisting bronchiectasis and smoking-related chronic obstructive lung disease, there was no evidence of airways obstruction, with a mean absolute FEV_1/VC ratio of

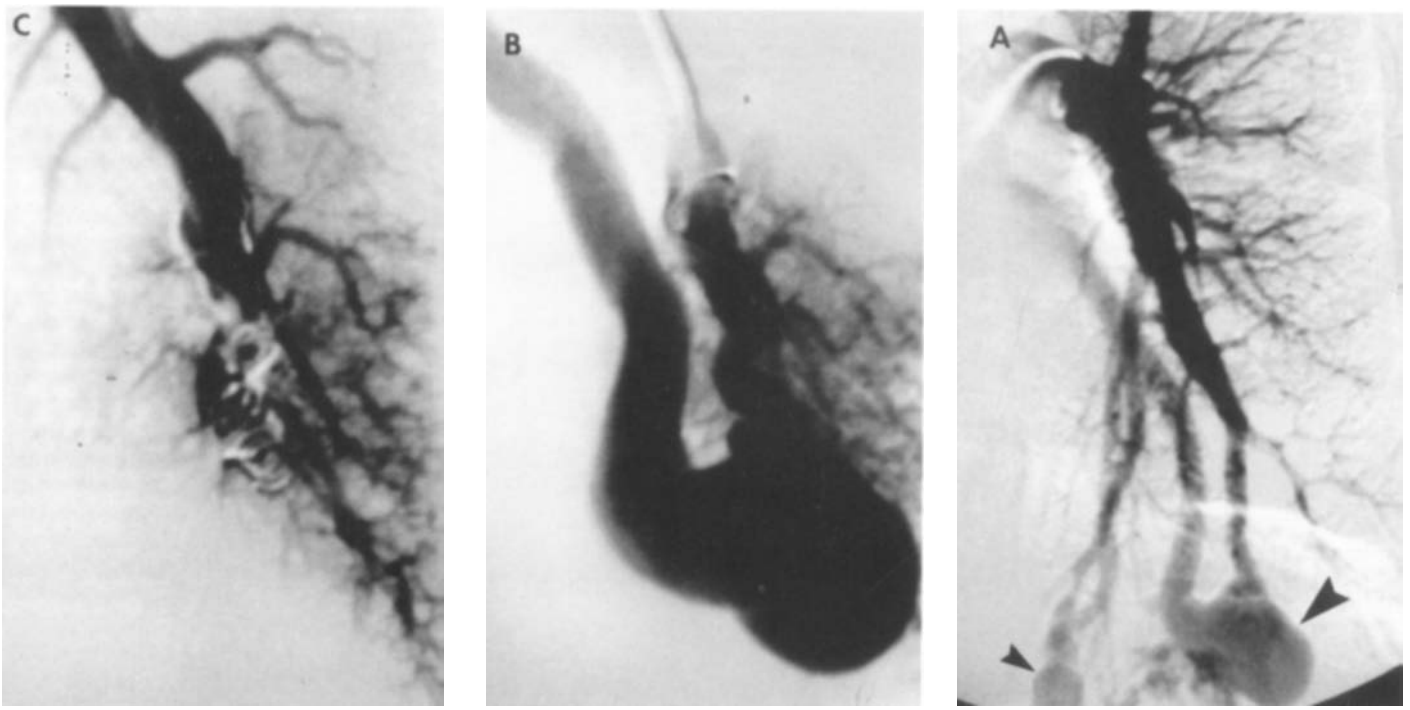

Fig. 1. (A) A selective left pulmonary angiogram demonstrates two large pulmonary arteriovenous malformations at the lung base (*arrows*). A single feeding vessel supplies each of these malformations with early opacification of single draining veins. (B) The catheter tip has been introduced into the feeding artery to the larger of the two malformations prior to embolization. Note that small vessels to normal lung arise just proximal to the malformation. (C) An angiogram performed following embolization with several steel coils demonstrates that the malformation is totally occluded. There is, however, good preservation of the small vessels to normal lung.

87 ± 3%. A significantly reduced D_{LCO} (< 80%) was seen in nine patients (mean percentage predicted value for all patients of 71, range 36 to 123).

Arterial Oxygen Saturation and Right-to-Left Shunt Fraction

All patients had a reduced resting Sa_{O_2} (< 95%) when measured supine (mean 86 ± 2%, range 67 to 95) (table 2). There was a detectable fall in the Sa_{O_2} in 13 patients when measured in the standing as opposed to supine position (mean 5.5%, range 1 to 11%), although in Patient 7, who had predominantly upper lobe PAVM, an increase in Sa_{O_2} from 67 to 76% was observed on standing. The mean right-to-left shunt measured in the supine position prior to embolization was 33 ± 3% (range 15 to 47%). A quadratic relationship between Sa_{O_2} and shunt fraction was observed [shunt fraction (%) = $-172 + 6.287\ Sa_{O_2} - 0.045\ Sa_{O_2}^2$) with 95% confidence limits of ± 13.5 shunt percent (figure 2A). There was a significant ($p < 0.05$) correlation between K_{CO} and shunt fraction ($r = -0.625$).

TABLE 2

PREEMBOLIZATION PULMONARY FUNCTION AND SHUNT FRACTION

Subject Number	FEV_1/VC (%)	% Predicted VC	% Predicted D_{LCO}	% Predicted K_{CO}	Supine Sa_{O_2} (%)	Shunt Fraction (%)
1	98	80	47	47	84	46
2	91	95	101	129	91	25
3*	75	100	101	121	95	30
4	80	87	63	80	91	30
5	83	113	123	112	94	15
6	116	80	96	88	74	47
7*	88	51	36	50	67	47
8	68	77	77	110	90	20
9*†	54	84	91	134	93	20
10	89	87	52	67	85	43
11	91	71	46	73	76	46
12*	84	81	39	52	87	37
13*‡	59	81	60	76	83	33
14	91	74	49	60	92	19
15	72	108	87	101	92	35
Mean	82.6	84.6	71.2	86.6	86.2	32.9
SD	15.1	14.8	26.2	28.5	8.0	10.9

* Previous lobectomy.
† Previous LLL and lingulectomy, RLL bronchiectasis.
‡ Previous LU lobectomy, smokes 20 cigarettes per day.

Exercise Testing

Exercise capacity was well preserved in the majority of patients, with a workload > 70% predicted achieved in 11 of the 15 subjects (mean work load for group [percentage predicted] 79 ± 6%, mean maximum heart rate 85 ± 3%) (table 3). This was despite marked and progressive arterial desaturation occurring in all except two patients (mean fall in Sa_{O_2} with maximum exercise 8 ± 2%, range −1 to 23%).

Effect of PAVM Embolization

The effect of embolization on VC, D_{LCO}, K_{CO}, exercise performance, and shunt is summarized in figures 3 and 4. There was no loss of lung volume, judged by a similar pre- and postembolization VC ($p = 0.64$, Wilcoxon signed rank test). Al-

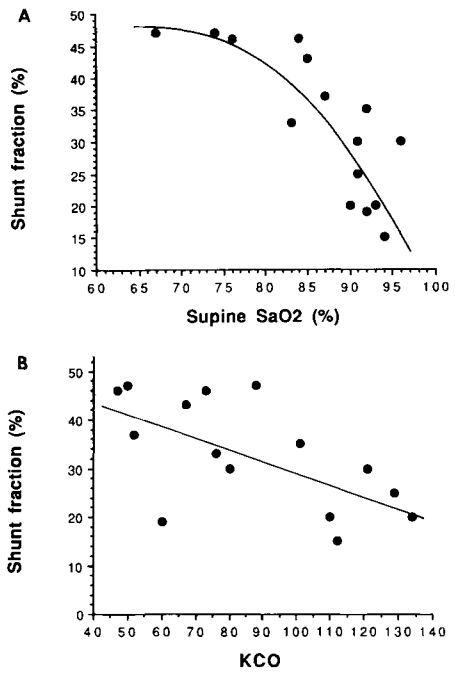

Fig. 2. Relationship between right-to-left shunt fraction and (A) arterial oxygen saturation (Sa_{O_2}) and (B) carbon monoxide transfer coefficient (KCO) in patients with PAVM prior to embolization. Shunt fraction and Sa_{O_2} were measured at rest and in the supine position.

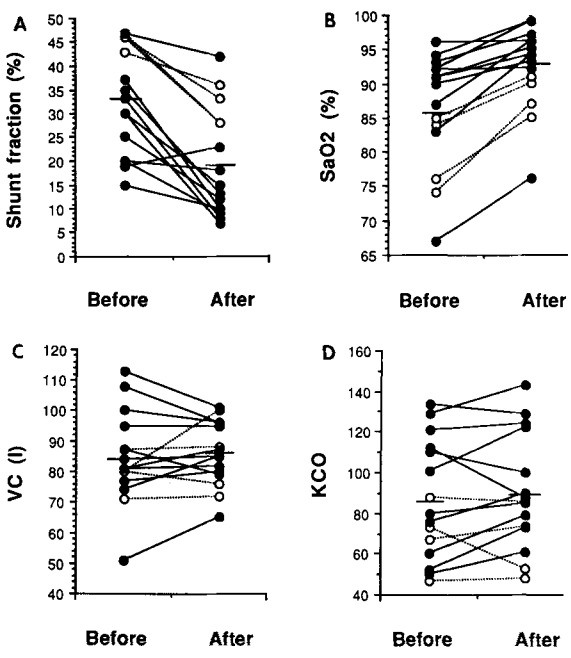

Fig. 3. Effect of percutaneous transcatheter embolization on (A) right-to-left shunt fraction ($p < 0.001$); (B) supine arterial oxygen saturation (Sa_{O_2}, $p < 0.002$); (C) vital capacity (VC); and (D) carbon monoxide transfer coefficient (KCO, $p > 0.05$). Postembolization measurements were undertaken 2 to 6 months after final embolization procedure. Patients with residual macroscopic PAVM remaining after their initial embolization in whom further procedures are planned, with horizontal lines indicating mean values (*open circles*).

though increases in the KCO were seen in 11 of the 15 patients, this did not reach statistical significance ($p = 0.27$). In general, an improvement in DLCO and KCO was most noticeable in the four patients with PAVM not associated with HHT, in whom the DLCO and KCO increased by 9 to 15% predicted and 14 to 21% predicted, respectively. The most consistent finding postembolization was a significant ($p < 0.001$) decrease in right-to-left shunt fraction, which improved from 33 to 19% (mean reduction in shunt 14 ± 2%, range 2 to 27%), with this residual value thought to reflect shunt through vessels not embolized, that is, < 3 mm diameter. Mean resting supine Sa_{O_2} also increased significantly ($p < 0.05$) from 86 to 92%. These values include data from four patients (1, 6, 10, and 11) in whom macroscopic PAVM remain, and further embolization is planned and therefore probably understate the benefits of this procedure. An increase in maximum exercise capacity was observed in eight patients (unchanged in the remaining), and despite this increase in work load, Sa_{O_2} during maximal exercise was likewise improved in all except one patient from a mean of 72 ± 5% pre-embolization to 79 ± 5% postembolization. Since cardiac output, oxygen delivery, and power output (W) are closely related, the product of work load and Sa_{O_2} at maximum exercise has been used as an index of exercise performance and increased in all except one patient following embolization ($p < 0.002$) (figure 4).

TABLE 3

EFFECT OF EMBOLIZATION ON EXERCISE PERFORMANCE

Subject Number	Maximum Workload (W)		Sa_{O_2} (%) at Maximum Exercise	
	Before	After	Before	After
1*	75	105	48	54
2	60	68	93	95
3	120	120	90	95
4	180	210	83	86
5	45	75†	92	96
6*	90	90	62	62
7	23	30	29	42
8	112	120	72	81
9	180	210	92	90
10*	150	150	66	69
11*	75	75	53	59
12	135	135	75	90
13	180	180	68	89
14	180	—‡	83	—‡
15	136	150	85	96
Mean	116.1	122.7	72.7	78.9
SD	51.1	51.9	18.1	17.4

* Further embolization procedures planned as a number of macroscopic PAVMs remain.
† Postembolization exercise test stopped because of frequent multifocal ventricular ectopics.
‡ No postembolization exercise test performed.

Discussion

As stated previously, the main reason for attempting to ablate all macroscopic PAVM in these patients, regardless of symptoms or absolute shunt size, is the high risk of systemic embolization. The high incidence of cerebrovascular events, including transient ischemic attacks, stroke, and cerebral abscess due to thrombus formed on, or passing through, these lesions, is now well recognized and is the principal determinant of the high mortality and morbidity rates of 11 to 30% and 26 to 33%, respectively, reported in previous large series (1, 2, 5). The slightly higher incidence of associated HHT in our patients (73%) compared to that observed in most series (30 to 50%) (2) may reflect our efforts to screen all first-degree relatives of patients with coexisting HHT since 10 to 15% of these sub-

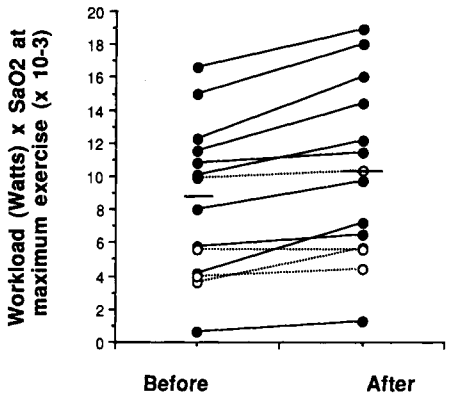

Fig. 4. Effect of percutaneous transcatheter embolization on exercise capacity in 14 patients using work load (W) × Sa_{O_2} (%) at maximum exercise as an index of exercise performance. Patients with residual macroscopic PAVM remaining after their initial embolization in whom further procedures are planned, with horizontal lines indicating mean values (*open circles*).

jects are found to have PAVM, with many of these previously unrecognized (5, 9, 21, 22).

The development of transcatheter embolization techniques has been a major advance in the effective management of patients with PAVM because it avoids the need for thoracotomy and allows the treatment of multiple, widespread lesions without sacrificing normal lung (3, 9–11). The angiography and embolization procedures were well tolerated in all subjects, and no long-term complications were encountered. In only three patients, all with multiple, widespread lesions, were more than two embolization sessions required to ablate all radiologically significant PAVM.

Preembolization pulmonary function tests demonstrated marked arterial oxygen desaturation at rest that failed to correct with 100% oxygen. This is characteristic of patients with anatomic right-to-left shunts. As previously documented (23), due to the mainly basal distribution of PAVM, shunt fraction and, hence, degree of arterial oxygen desaturation increase in the upright position. Although not examined in this study, it is also expected that shunt varies according to lung volume (24) since, at full inspiration, vascular resistance in the normal pulmonary capillary bed increases, resulting in greater blood diversion through the low-resistance shunt vessels.

The calculation of right-to-left shunt using the 100% oxygen method allows rapid and accurate measurement of anatomic shunt with effective exclusion of any contribution of ventilation-perfusion mismatch. It does, however, have the minor disadvantage of measuring additionally postpulmonary shunt, the latter due to the admixture of oxygenated blood with venous blood from Thebesian, bronchial, and mediastinal vessels. The 100% oxygen method may also overestimate the true anatomic shunt, especially in older subjects, owing to incomplete nitrogen washout in areas of very low ventilation. Consequently, slightly lower shunt values are obtained in normal subjects when this method is used during exercise compared to the usual resting supine position (25). On the other hand, the 100% oxygen method may underestimate shunt fraction in patients with multiple microscopic arteriovenous connections since these small vessels may participate in gas exchange when the patient is breathing 100% oxygen (26). Nevertheless, the accuracy of the 100% oxygen method in estimating shunt across a wide range of values in patients with PAVM has been shown previously by demonstrating a close correlation ($r = 0.993$) between shunt values obtained using this method and those obtained using a radioisotopic method in which the detection of [$^{99}Tc^{m}$]-albumin microspheres passing into the systemic circulation following intravenous injection provides an index of right-to-left shunt (27).

Polycythemia is also a characteristic feature of patients with PAVM (2, 12). The relatively low occurrence of this finding in our study may reflect the preponderance of patients with HHT in whom occult gastrointestinal blood loss can prevent the development of polycythemia. In earlier studies hemoglobin values of up to 24 g/dl and hematocrits up to 84% have been reported, reflecting an increase in red cell mass with normal or near normal plasma volumes (12). Polycythemia increases the risk of stroke even further and strengthens the argument for early intervention in these patients to reduce the degree of abnormal shunt and hence improve oxygenation.

The most significant and consistent physiologic change observed following embolization was a decrease in shunt fraction from 33 to 19% and a corresponding increase in resting supine Sa_{O_2} from 86 to 92%. Allowing for a right-to-left shunt of up to 3% in normal subjects when measured using the 100% oxygen technique (20), this indicates that embolizing all angiographically visible PAVM with a feed vessel diameter > 3 mm reduces the shunt fraction by approximately 50%. The surprisingly large shunt that remained in all patients, including those without evidence of associated HHT, most likely reflects blood flow through residual small lesions and microscopic PAVM. Recently White and coworkers (9) reported that, in a group of patients with PAVM embolized using detachable silicone balloons, resting supine Pa_{O_2} increased from 58 to 75 mm Hg, with standing Pa_{O_2} increasing from 47 to 68 mm Hg, also implying the persistence of a significant residual right-to-left shunt following embolization. It is possible that following occlusion of the major shunt vessels the resulting elevation of pulmonary vascular resistance (13) increases the shunt fraction through the smaller lesions. On the other hand, the risk of paradoxical embolization is greatest from the macroscopic PAVM, which can all be successfully ablated.

There was no overall change in the VC following embolization, but interestingly, in three patients an increase > 10% was observed, suggesting that in certain circumstances PAVM may act as space-occupying lesions. The initially low D_{LCO} and K_{CO} observed in the majority of these patients could not be accounted for by previous surgery and suggests impaired pulmonary capillary blood flow to normal lung secondary to vascular steal through the PAVM. An improvement in diffusing capacity was most marked in the four patients without evidence of associated HHT, with increases in the K_{CO} of between 14 and 21% of predicted. The failure to detect similar consistent improvements in diffusing capacity following embolization of the patients with HHT, despite similar reductions in shunt fraction, is unclear and was the only physiologic parameter identified in this study, measured either before or after embolization, that distinguished the patients in these two groups.

The extremely well-preserved exercise capacity, despite significant resting arterial oxygen desaturation and further desaturation on exercise, has not been recognized previously. One of the reasons for this finding may relate to the low pulmonary vascular resistance and preserved or increased cardiac output observed in patients with PAVM (12). Certainly in animal models, opening experimentally produced pulmonary arteriovenous fistulas results in significant increases in stroke volume and cardiac output and a fall in mean pulmonary arterial pressure (13). This allows an increase in cardiac output during exercise, with preservation of oxygen delivery to the tissues despite marked arterial oxygen desaturation. Pa-

tients who are hypoxic for other reasons often have secondary pulmonary hypertension that prevents a normal increase in cardiac output on exercise. Other factors, such as the level of anaerobic metabolism or position of the oxygen dissociation curve, may also contribute. The bias and precision of the Ohmeda Biox oximeter has been validated previously and shown to have an accuracy of ± 2.2% at an $Sa_{O_2} > 80\%$ and ± 5% at an $Sa_{O_2} < 80\%$ (18). The reasons for the deteriorating Sa_{O_2} observed in these patients during exercise is not entirely clear. Although a fall in mixed venous oxygen content, which invariably occurs on exercise, may be sufficient explanation, it is also possible that the right-to-left shunt fraction increases with exercise owing to a modest increase in pulmonary vascular resistance related to hyperpnea during exercise. Exercise testing was repeated in 14 patients 2 to 6 months after PAVM embolization; compared to preembolization values, maximal exercise capacity increased in 8 with no change in 6, and higher Sa_{O_2} values were recorded during maximal exertion in the majority (12 of 14 patients) despite a greater work load.

Simple exercise testing and calculation of shunt fraction therefore appear to be useful methods for assessing the effects of PAVM embolization and often indicate the presence of a significant residual shunt that may not have been fully apparent from the resting Sa_{O_2}, especially if the latter is measured supine. Hence in the group of patients with postembolization resting Sa_{O_2} values > 95%, all except one desaturated significantly on exercise and were subsequently shown to have shunts of between 7 and 13%. It may therefore be inappropriate to rely on resting Sa_{O_2}, or indeed changes in CO diffusing capacity, as the principal or only determinants of the effectiveness of embolization.

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