Pulmonary Arteriovenous Malformations: Effect of Embolization on Right-to-Left Shunt, Hypoxemia, and Exercise Tolerance in 66 Patients

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OBJECTIVE. This study assessed the effect and safety of percutaneous transcatheter coil embolization of pulmonary arteriovenous malformations.

MATERIALS AND METHODS. In 58 (88%) of 66 patients, all malformations with feeding vessels greater than or equal to 3 mm in diameter were embolized with steel coils. Arterial oxygen saturation at rest and exercise, intrapulmonary right-to-left anatomic shunt fraction (^{99m}Tc-macroaggregate injection), maximum exercise capacity (incremental work rate test), and pulmonary function were measured before and after embolization. Complications were analyzed.

RESULTS. Three categories of patients were identified. Patients in group 1 (27%) had complete occlusion of all angiographically visible pulmonary arteriovenous malformations; patients in group 2 (61%) had complete occlusion of all malformations with feeding vessels greater than or equal to 3 mm in diameter, but with smaller lesions persisting; and patients in group 3 (12%) had incomplete embolization, with feeding vessels greater than or equal to 3 mm in diameter remaining. The mean right-to-left shunt after embolization was least in group 1 (7%), intermediate in group 2 (10%), and greatest in group 3 (19%). Arterial oxygen saturation and right-to-left shunt fraction returned to normal levels (>96% and <3.5%, respectively) in 33% of patients. A significant improvement occurred after embolization in carbon monoxide diffusing capacity per unit of alveolar volume and in exercise capacity in 16 and 10 patients, respectively. In 93 procedures, 12 complications (13%) occurred.

CONCLUSION. Coil embolization of pulmonary arteriovenous malformations is effective in reducing right-to-left anatomic shunt fraction and in improving arterial oxygenation. Coil embolization of pulmonary arteriovenous malformations is well tolerated and has a low complication rate.

Pulmonary arteriovenous malformations are congenital lesions that provide a direct communication between pulmonary arteries and veins without an intervening capillary bed; they range from complex vascular structures supplying and draining a bulbous aneurysmal sac [1] to small-caliber telangiectatic vessels. Sporadic pulmonary arteriovenous malformations are rare; most occur in association with the inherited disorder, hereditary hemorrhagic telangiectasia (Osler-Weber-Rendu syndrome), in which there is a 30% incidence of pulmonary arteriovenous malformations [2–4]. Because the European incidence of hereditary hemorrhagic telangiectasia incidence exceeds one in 10,000 [5–7], the United Kingdom national incidence of pulmonary arteriovenous malformations may be estimated to be about 2000.

Complications relating to pulmonary arteriovenous malformations are common [2]; most can be attributed to the intrapulmonary right-to-left shunt, which in severe cases may exceed 40% of the cardiac output. Hypoxemia is common but is usually well tolerated by the patient because of the attendant low pulmonary vascular resistance. Nevertheless, cerebral abscesses, cerebrovascular accidents, and transient ischemic attacks due to paradoxic embolism through the pulmonary arteriovenous malformations result in considerable morbidity and mortality [8–11]. Although individual pulmonary arteriovenous malformations were once treated by surgical resection, multiple lesions are likely to develop over time in most individuals with hereditary hemorrhagic telangiectasia. Transcatheter embolization has transformed the outlook for patients

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and is now considered the treatment of choice [12]. To reduce the incidence of paradoxic embolism, all pulmonary arteriovenous malformations with feeding vessels amenable to endovascular occlusion should be so treated, and antibiotic prophylaxis should be administered for dental and surgical procedures in patients with residual shunts [2, 13].

Articles about embolization provide evidence for regression of the pulmonary arteriovenous malformation sac [14], reduction in the right-to-left shunt [15–20], and improvement in hypoxemia [2, 15, 18–24]. However, published series also reveal varying efficacy and complications of treatment, according to the center where the study was performed. In this article, we present 66 patients who have not been described in any study. This series presents new therapeutic protocols and highlights further improvement in the efficacy of treatment and reductions in the incidence of embolization-associated complications. We have again shown a significant improvement in KCO (DL/VA) (the diffusing capacity for carbon monoxide per unit of alveolar volume) in a subgroup of treated patients in whom KCO before embolization was less than 90% of the predicted value. In addition, we have introduced a new categorization for pulmonary arteriovenous malformation patients to provide a suitable framework for long-term follow-up studies.

Materials and Methods

The study group comprised 66 consecutive patients with pulmonary arteriovenous malformation who underwent coil embolization at Hammersmith Hospital between March 1994 and July 1999. The patients were 45 females and 21 males having an average age of 44.4 years (range, 13–77 years). Fifty-five patients (83.3%) had hereditary hemorrhagic telangiectasia; forty-nine (74%) experienced epistaxes. Among the female patients, 23 (51%) had children before presentation, 18 (40%) did not have children, and four (9%) became pregnant during follow-up. The patients included 19 smokers, six ex-smokers, and 41 nonsmokers. Before inclusion in this treatment series, 16 patients (24%) had undergone previous treatment of pulmonary arteriovenous malformations as follows: by embolization at our institution before March 1994 (n = 7), by embolization at another hospital (n = 4), by surgical resection (n = 3), by cauterization (n = 1), and by lobectomy (n = 1). All were subjected to detailed history inquiries, examination, and investigations as delineated in the following text.

Pulmonary Function Tests

Standard pulmonary function tests were performed, including forced expiratory volume in 1 sec (FEV_1), vital capacity, single-breath diffusing capacity for carbon monoxide (DLCO), and diffusing capacity for carbon monoxide per unit of alveolar volume (KCO [DL/VA]). The mean values for these measurements were corrected for the current hemoglobin concentration and expressed as a percentage of the predicted value.

Arterial oxygen saturation (SaO_2) was measured with the patient breathing room air using a pulse oximeter (Biox 3740; Ohmeda, Hatfield, Hertfordshire, UK) and an ear probe in the standing and the supine positions (each for 10 min, with recordings every 60 sec and the result expressed as the mean of the last four readings). SaO_2 was also measured at maximal exercise on a cycle ergometer (Ergomed 840 cycle ergometer; Siemens, Bracknell, Berkshire, United Kingdom) using a 15–30 W/min incremental protocol. For patients unable to cycle, the distance walked on a level surface in 3 min was measured with a recording of SaO_2 and pulse rate at the end of the walk.

Right-to-Left Shunt Assessment

Right-to-left shunt was measured by the IV injection of ^{99m}Tc-labelled albumin macroaggregates followed by gamma camera imaging. The principle and method of this technique have been described previously [25, 26]. In brief, calculations of the shunt fraction were made using the counts in the right kidney, corrected for attenuation, and expressed as a percentage of the injected dose, with the right-to-left shunt expressed as 10 times this value assuming the right kidney received 10% of the cardiac output (kidney-dose method). A second method calculated the right kidney counts as a proportion of the counts over the lungs (kidney–lung method). For each subject, the mean of the measurements obtained using kidney-dose and kidney–lung methods was used. For some patients, multiple measurements were recorded on different occasions. The mean right-to-left shunt measurement before embolization was taken from the average of the earliest recorded results; the mean shunt measurement after embolization was taken from the average of the latest recorded results.

Embolization Procedure

The same person performed all pulmonary embolizations. Prophylactic antibiotics (500 mg of vancomycin) were administered 1 hr before and 8 hr after each procedure. Diagnostic pulmonary arteriograms preceded pulmonary arteriovenous malformation embolization in a single session. If required, patients were readmitted for further elective embolization after approximately 3 months; each embolization procedure lasted approximately 2–2.5 hr.

Bilateral pulmonary arteriography in frontal and oblique projections was initially performed in all patients after measurement of the pulmonary artery pressure. The pigtail catheter used for these arteriograms was then exchanged for a Headhunter I catheter (Cordis; Ascot, Berkshire, United Kingdom), and embolization of the feeding vessels to the individual pulmonary arteriovenous malformations was achieved with metallic coils.

The technique of embolization has been described [27] and involves placing coils as close as possible to the neck of the malformation in an attempt to avoid the occlusion of normal pulmonary artery branches. Coils of a size depending on the diameter of the feeding artery were deployed in each vessel until complete occlusion was obtained. Most of the coils used in this series were mechanically detachable (Jackson Detachable Coil; William Cook Europe, Bjaeverskov, Denmark) [28]. In three patients, packing of the venous sac with coils [29] was performed because the anatomy of the arteriovenous malformations in these individuals precluded conventional embolization; in another two patients, embolization of two large high-flow pulmonary arteriovenous malformations was achieved with coils inserted through the lumen of a standard occlusion balloon catheter that was temporarily inflated to obliterate flow in the feeding vessel.

Follow-Up

Patients were followed up in a dedicated pulmonary arteriovenous malformation clinic 3 months after their final embolization and annually thereafter. Clinical examination, pulmonary function tests, and radionuclide studies were performed. The average period of follow-up after embolization was 27.3 months (range, 0–67 months).

Statistical Analysis

The data were analyzed using the statistical software STATA (version 6; Stata, College Station, TX). To identify associations in the data, we used the chi-square test for categoric variables. The nonparametric Wilcoxon's matched pairs signed rank test was used to compare continuous measurements. To compensate for multiple comparison tests, only p values of less than 0.01 were considered statistically significant.

Values obtained before and after embolization do not include repeated measurements taken of individuals who underwent multiple procedures. The value before embolization corresponds to the subject's earliest recorded value and the value after embolization corresponds to the subject's latest recorded value, resulting in only one set of values per subject.

Results

Patient Assessment Before Embolization

At presentation, the clinical features of the patients were similar to those in previous series [8–11, 15–19, 21, 24, 30–35] (Table 1). Overall, the mean FEV_1, vital capacity, DLCO, and KCO values before embolization were within published normal ranges [36]. Before embolization, the supine mean SaO_2 was 92.3% ± 0.6% (standard error of the mean) and erect mean SaO_2 was 90.4% ± 0.7%. The maximum exercise capacity varied widely, ranging from a 120-m walk to 270 W (mean, 120 W) on the cycle ergometer. Before embolization, the mean SaO_2 at maximum exercise was 90% ± 1%. The mean right-to-left shunt measured in the supine position before embolization was 12.8% ± 1%.

TABLE 1 Features at Presentation of Patients with Pulmonary Arteriovenous Malformations

Feature	This Study		Previous Studies[a]		
	No.	%	Mean (%)	Range (%)	No.
Respiratory phenomena					
Dyspnea	37	56	47	27–71	427
Chest pain	12	18	12	6–17	132
Hemoptysis	6	9	11	4–18	413
Hemothorax	2	3	<1	0–2	129
Asymptomatic	31[b]	47	49	25–58	197
Cyanosis	19	29	30	9–73	209
Clubbing	13	20	36	6–68	201
Bruit	8	12	49	25–58	197
Embolic phenomena					
Cerebral abscess	11	17	9	0–25	302
CVA[c]	10	15	—	—	—
TIA[c]	22	33	—	—	—
CVA or TIA[c,d]	28	42	24	11–55	335
CVA, TIA, or cerebral abscess[d]	34	51	—	—	—
Peripheral abscess	2[e]	3	—	—	—
Migraine	25	38	45	43–48	121

Note.—CVA = cerebrovascular accident, TIA = transient ischemic attack, dash (—) indicates not available.

[a](2, 8–11, 15–19, 24, 30–35) reviewed in [2].

[b]Two asymptomatic patients had both clubbing and cyanosis, a third had cyanosis, and a fourth had audible bruit.

[c]Nonembolic sources were possible in 10 patients with attendant migraine; one patient with a cerebral arteriovenous malformation hemorrhage was excluded.

[d]Some patients had more than one event.

[e]One renal, one gluteal.

Although hypoxemia provides a strong erythropoietic stimulus, in many patients the resultant secondary polycythemia was masked by concurrent nasal or gastrointestinal hemorrhage caused by underlying hereditary hemorrhagic telangiectasia. Eighteen patients (27%) were polycythemic (male, hemoglobin >17.7 g/dL; female, hemoglobin >15.2 g/dL) at some stage. Three patients required venesection. Polycythemia was seen in 33% (15/45) of females and 14% (3/21) of males.

Ten patients received blood transfusions. No significant sex difference was noted in the incidence of anemia (females: 13/45, 29%; males: 9/21, 43%; chi-square test = 1.26, $p = 0.262$).

Embolization

Ninety-three procedures were performed in 66 patients (range, one to four procedures; mean, 1.4 procedures per patient). Forty-eight patients underwent a single procedure, and 18 patients underwent multiple procedures. A total of 225 pulmonary arteriovenous malformations (right lung, 125 [56%]; left lung, 100 [44%]) were embolized. The zonal distribution of the embolized lesions was 11% in the upper zone, 29% in the mid zone, and 60% in the lower zone. A mean of 2.5 pulmonary arteriovenous malformations (range, one to seven malformations) were occluded with an average of 10 metallic coils (range, one to 39 coils) per procedure. The feeding vessels ranged from 2 to 12 mm in diameter (mean, 6 mm). Mean pulmonary artery pressure before embolization was 15.3 mm Hg (range, 8–36 mm Hg), and mean systolic and diastolic pressures were 26 and 8.8 mm Hg, respectively.

The patients were divided into three groups. Group 1 patients (n = 18, 27%) experienced complete occlusion of all angiographically visible pulmonary arteriovenous malformations. Group 2 patients (n = 40, 61%) experienced complete occlusion of all pulmonary arteriovenous malformations with feeding vessels greater than or equal to 3 mm diameter, but with smaller lesions persisting on angiography. In group 3 patients (n = 8, 12%), embolization was incomplete and feeding vessels larger than 3 mm remained. Four patients are awaiting further embolization, and one has since died of unrelated causes. In the remaining three group 3 patients, embolization was incomplete because of increasing pulmonary artery pressures (n = 1) or because of the risk of occluding pulmonary artery branches that supply large amounts of normal lung (n = 2).

TABLE 2 Arterial Oxygen Saturation, Maximum Workload, and Intrapulmonary Shunt Size Expressed as Medians Before and After Embolization in All Three Groups Combined

Measurement	Arterial Oxygen Saturation (%)				Workload (W) (n = 46)	Right-to-Left Shunt (%) (n = 55)
	Supine (n = 65)	Erect (n = 65)	Supine Minus Erect (n = 65)	Maximum Exercise (n = 48)		
Before embolization						
Median	94	93	1	92	120	10.5
Interquartile range	91, 96	87.5, 95	0, 3	87.3, 94	75, 150	7.2, 19.5
Difference, after and before embolization						
Median	2	3.5	–1.5	3.5	0	–5.7
95% Confidence limits	1, 3	2.5, 4.5	–2, –0.5	2, 5	0, 7.5	–7.7, –4.3
p[a]	<0.0001	<0.0001	0.0007	<0.0001	0.073	<0.0001

[a]Using Wilcoxon's matched pairs signed rank test.

One potentially serious complication occurred in the 93 procedures when a 5-mm coil migrated through the pulmonary arteriovenous malformation into the left popliteal artery, from which it was successfully snared and removed without any sequelae. Five patients experienced mild central chest pain during the procedure; in four patients this pain was accompanied by elevation of the ST segment on an EKG, and the pain was rapidly relieved by sublingual nitrate and 100% oxygen. Another patient had mild chest discomfort, most likely musculoskeletal in origin, that was relieved by 100% oxygen. In two patients, a small part of the normal lung parenchyma had to be sacrificed. After embolization, three patients experienced pleuritic chest pain that resolved with nonsteroidal antiinflammatory agents. One patient had a small hemoptysis associated with an area of alveolar shadowing that occurred at the lung base during embolization and that was probably caused by the rupture of a small vessel during coil occlusion. The patient was well and pain-free the next day and has experienced no further hemoptysis.

After Embolization

After maximal embolization, significant improvement was seen in the Sa_{O_2} in both postures, on maximal exercise, and in the right-to-left shunt in each group (Tables 2–5). Overall, using our previously published criteria [37], the right-to-left shunt returned to normal (<3.5%) in 22 patients (33%); erect Sa_{O_2} was greater than 96% in 28 patients (42%). A significant improvement occurred in Sa_{O_2} on maximal exercise testing (p < 0.0001) overall, but no significant improvement in workload was achieved in any of the three groups. However, for groups 1 and 2 combined, a significant difference (p = 0.004) was noted between the workload measurements before and after embolization, although only 10 (22%) of 46 patients actually improved, and the maximum improvement observed was only 45 W.

No significant change was seen in the mean FEV_1, vital capacity, D_{LCO}, and K_{CO} after embolization (Table 6). In the subgroup of patients (n = 16) with K_{CO} before embolization of less than 90% of the predicted value, all except two showed improvement after embolization. In these 16 patients, embolization resulted in a statistically significant improvement in K_{CO} (p = 0.004, Wilcoxon's matched pairs signed rank test).

Follow-Up

Pulmonary arteriovenous malformations.—Three patients had successful pregnancies after embolization of pulmonary arteriovenous malformations. All these patients experienced considerable deterioration in right-to-left shunt, arterial oxygenation, and exercise capacity postpartum. Angiograms obtained after delivery showed enlargement of the residual lesions that were successfully embolized in two patients. In one patient, the pulmonary arteriovenous malformations were considered too

TABLE 3 **Arterial Oxygen Saturation, Maximum Workload, and Intrapulmonary Shunt Size Expressed as Medians Before and After Embolization in Group 1**

Measurement	Arterial Oxygen Saturation (%)				Workload (W) (n = 12)	Right-to-Left Shunt (%) (n = 13)
	Supine (n = 18)	Erect (n = 18)	Supine Minus Erect (n = 18)	Maximum Exercise (n = 12)		
Before embolization						
Median	95.5	95	0	94	135	8
Interquartile range	94, 97	92.8, 96.3	–0.3, 2	90.3, 95.8	97.5, 202.5	4.8, 14.2
Difference, after and before embolization						
Median	1.5	2	–1	2.5	0	–6.9
95% Confidence limits	0.5, 2.5	1, 3.5	–2, 0	0, 5	0, 7.5	–11.2, –3.1
p [a]	0.004	<0.001	0.082	0.044	0.084	0.0015

Note.—Patients in group 1 had complete occlusion of all angiographically visible pulmonary arterial malformations.

[a] Using Wilcoxon's matched pairs signed rank test.

TABLE 4 **Arterial Oxygen Saturation, Maximum Workload, and Intrapulmonary Shunt Size Expressed as Medians Before and After Embolization in Group 2**

Measurement	Arterial Oxygen Saturation (%)				Workload (W) (n = 31)	Right-to-Left Shunt (%) (n = 36)
	Supine (n = 39)	Erect (n = 39)	Supine Minus Erect (n = 39)	Maximum Exercise (n = 32)		
Before embolization						
Median	93	92	2	92	120	10.6
Interquartile range	92, 96	87, 95	0, 3	88.5, 84	75, 150	7.2, 19.4
Difference, after and before embolization						
Median	2.5	3.5	–1.5	3.5	0	–6.2
95% Confidence limits	1.5, 3.5	2, 5.5	–2.5, –0.5	2, 5	0, 15	–8.8, –4.5
p [a]	<0.0001	<0.0001	0.011	<0.0001	0.017	<0.0001

Note.—Patients in group 2 had complete occlusion of all malformations with feeding vessels ≥ 3 mm diameter, but with smaller lesions persisting.

[a] Using Wilcoxon's matched pairs signed rank test.

TABLE 5 Arterial Oxygen Saturation, Maximum Workload, and Intrapulmonary Shunt Size Expressed as Medians Before and After Embolization in Group 3

Measurement	Arterial Oxygen Saturation (%)				Workload (W) (n = 4)	Right-to-Left Shunt (%) (n = 6)
	Supine (n = 8)	Erect (n = 8)	Supine Minus Erect (n = 8)	Maximum Exercise (n = 5)		
Before embolization						
Median	89.5	84	5.5	80	97.5	20.85
Interquartile range	82.5, 92.5	75.8, 88.3	2.3, 7.8	60, 84.5	52.5, 120	14.1, 26.9
Difference, after and before embolization						
Median	1.75	6	–4	8	–3.75	–2.8
95% Confidence limits	–9, 6.5	0.5, 13.5	–14, 1.5	—	—	–5.05, 0.8
p [a]	0.477	0.035	0.181	0.138	0.853	0.059

Note.—Patients in group 3 had incomplete embolization with feeding vessels ≥ 3 mm diameter remaining. Dash (—) indicates too few subjects to calculate.

[a]Using Wilcoxon's matched pairs signed rank test.

small (<3 mm in diameter) and too numerous for further embolization.

General.—Two deaths occurred, both unrelated to pulmonary arteriovenous malformations. One patient had a cardiorespiratory arrest after appendicular surgery. In the second patient, a postmortem examination revealed pneumonia. One patient with a cerebral arteriovenous malformation developed an intracerebral hematoma during follow-up that led to considerable disability.

Discussion

Pulmonary arteriovenous malformations are high-flow, low-resistance vascular shunts. Their treatment by steel coil (or balloon) embolization is one of the more difficult procedures in interventional radiology. Technique is critical, so we have outlined our protocols before, during, and after the embolization, as well as technical advances for dealing with particularly difficult pulmonary arteriovenous malformations. In this series, to our knowledge the largest to date with full physiologic assessment, we have shown that steel coil embolization is associated with a low morbidity and a good outcome in terms of right-to-left shunt reduction.

Good though present treatment is, small residual lesions remain in 60% of patients (Table 4, group 2). These lesions stem from pulmonary arteriovenous malformations whose feeding vessels are too small (<3 mm in diameter) to be embolized with current technology. These patients continue to be at risk from paradoxic embolization and neurologic sequelae, although the risk is significantly less than it was before treatment. Nevertheless, antibiotic prophylaxis before dental procedures and surgical treatment should continue.

Interventional Techniques

By far most pulmonary arteriovenous malformations can be successfully treated by conventional embolization whereby coils are placed at the neck of the malformation immediately proximal to the dilated aneurysmal sac (Fig. 1). It is important to achieve a distal occlusion, if possible, for the following reasons: First, vessels that arise from the feeding vessel that supplies the normal lung, which may not be visualized on arteriography performed before embolization because of a steal effect through a high-flow shunt, will be preserved (Fig. 1), and this portion of the lung will maintain its ability to participate in gas exchange. Although preserving vessels may not be clinically important in patients with one or two pulmonary arteriovenous malformations whose remaining lung is otherwise normal, it is likely to be relevant in those who have numerous shunts and a reduced amount of normal pulmonary parenchyma. Preservation of these branches may be one of the factors that reduces the incidence of pleuritic chest pain after embolization, which has been reported to occur in 10% or more of individuals undergoing pulmonary arteriovenous malformation embolization in some series [18, 21]. Our incidence of this complication was only 3%, which may reflect the great importance we attach to distal embolization. Second, distal occlusion may reduce the likelihood of continued perfusion of the venous sac by normal bronchopulmonary anastomoses, although the clinical importance of this is unknown.

Packing the venous sac.—Only five of 225 pulmonary arteriovenous malformations could not be treated by conventional coil occlusion; three were embolized by packing the venous sac with coils (Fig. 2). This technique was required when a very short or wide neck precluded embolization because of the risk of occlusion of large pulmonary artery branches that supply normal lung. Coils of appropriate size were therefore placed in the venous sac to provide a frame on which smaller coils could be used to completely occlude the neck. This form of embolization is not appropriate for most pulmonary arteriovenous malformations because of the theoretic risk of sac rupture and an increased possibility of

TABLE 6 Pulmonary Function Test Results Before and After Embolization of Pulmonary Arteriovenous Malformations in 60 Patients

Measurement	FEV_1	Vital Capacity	D_{LCO}	K_{CO} (D_L/V_A)
Before embolization				
Median	93.5	97.5	89.5	96.5
Interquartile range	79.5, 103.5	86, 108.5	75.5, 100.8	83.3, 113.3
Difference, after and before embolization				
Median	0.45	0.5	2	1.5
95% Confidence limits	–1.4, 2	–0.5, 2.5	–3, 6	–2.5, 5.5
p [a]	0.74	0.31	0.47	0.48

Note.—FEV_1 = forced expiratory capacity in 1 sec, D_{LCO} = single-breath diffusing capacity for carbon monoxide, K_{CO} (D_L/V_A) = diffusing capacity for carbon monoxide per unit of alveolar volume.

[a]Using Wilcoxon's matched pairs signed rank test.

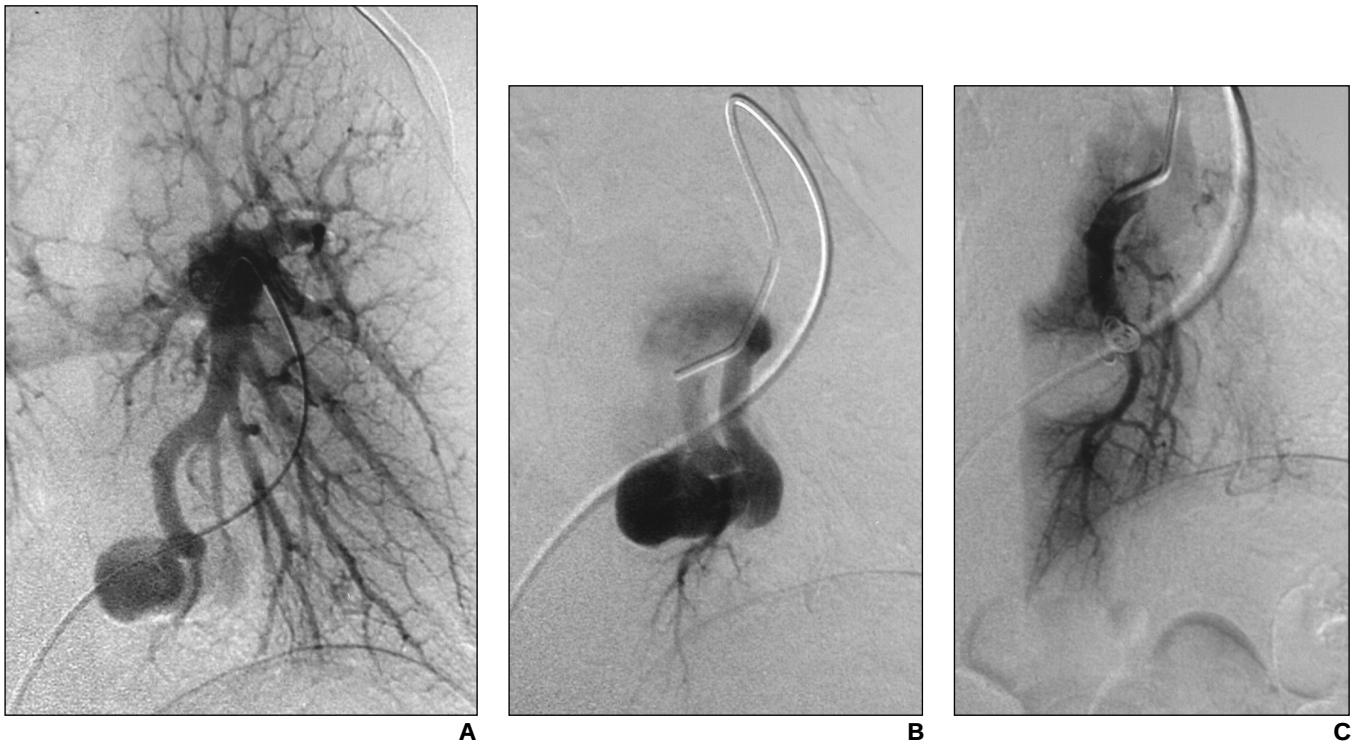

Fig. 1.—52-year-old woman with single left basal pulmonary arteriovenous malformation.
A, Selective left pulmonary arteriogram in right anterior oblique projection shows basal pulmonary arteriovenous malformation arising from segmental basal branch.
B, Selective angiogram with catheter in segmental basal pulmonary artery branch shows rapid arteriovenous shunting and poor filling of distal pulmonary artery branches because of steal effect.
C, After selective embolization of feeding vessel to pulmonary arteriovenous malformation, angiogram shows obliteration of arteriovenous shunting and preservation of normal peripheral pulmonary artery branches. Note improved filling of these vessels and of proximal branches that did not fill before embolization, as well as "negative" filling defect of aneurysmal sac.

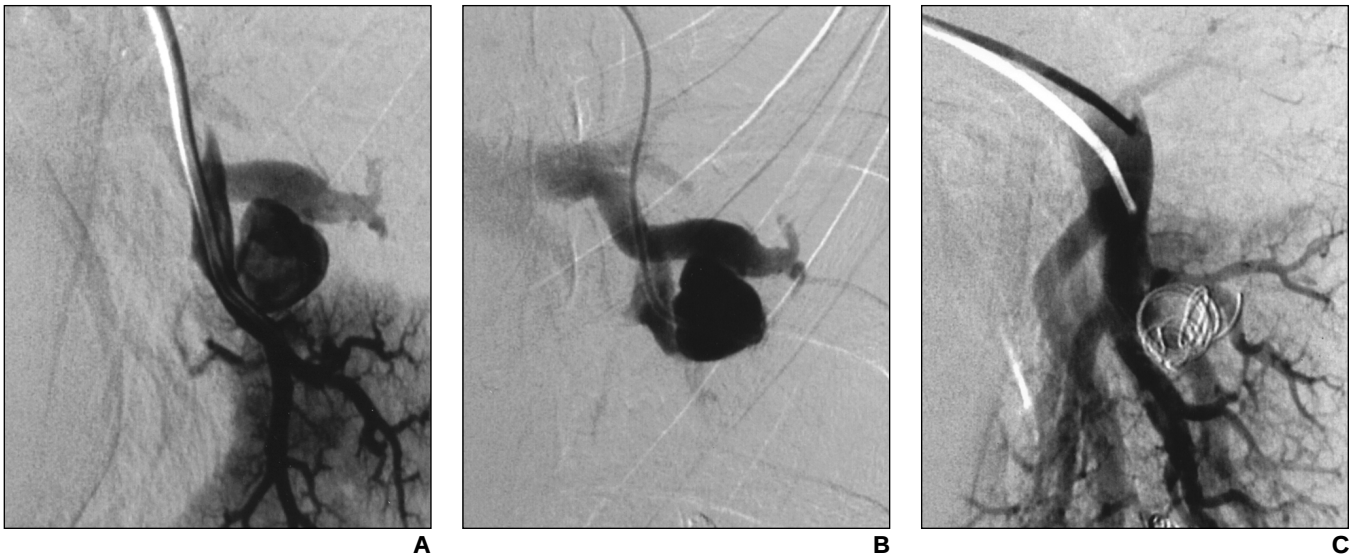

Fig. 2.—48-year-old woman with large pulmonary arteriovenous malformation.
A, Selective angiogram of segmental left basal pulmonary artery branch shows large arteriovenous malformation sac arising directly from side wall of proximal portion of this vessel with no identifiable neck. Conventional embolization of this malformation by occlusion of feeding artery would involve occlusion of large segment of normal lung.
B, Arteriogram shows that sac has been catheterized. Rapid shunting is seen into draining pulmonary vein.
C, Arteriogram after embolization shows metallic coils placed in sac to achieve occlusion while preserving parent vessel and distal normal pulmonary artery branches.

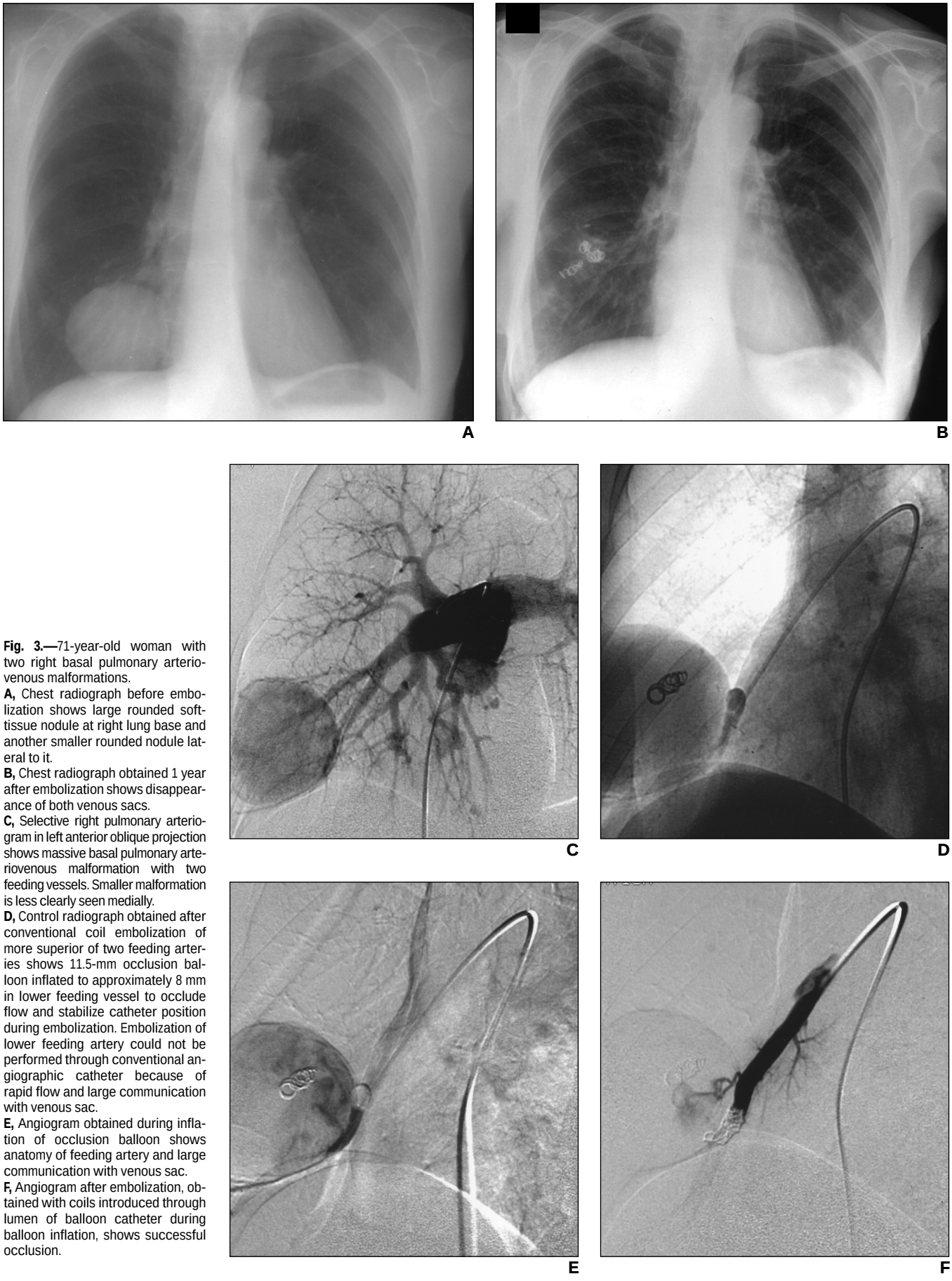

Fig. 3.—71-year-old woman with two right basal pulmonary arteriovenous malformations.
A, Chest radiograph before embolization shows large rounded soft-tissue nodule at right lung base and another smaller rounded nodule lateral to it.
B, Chest radiograph obtained 1 year after embolization shows disappearance of both venous sacs.
C, Selective right pulmonary arteriogram in left anterior oblique projection shows massive basal pulmonary arteriovenous malformation with two feeding vessels. Smaller malformation is less clearly seen medially.
D, Control radiograph obtained after conventional coil embolization of more superior of two feeding arteries shows 11.5-mm occlusion balloon inflated to approximately 8 mm in lower feeding vessel to occlude flow and stabilize catheter position during embolization. Embolization of lower feeding artery could not be performed through conventional angiographic catheter because of rapid flow and large communication with venous sac.
E, Angiogram obtained during inflation of occlusion balloon shows anatomy of feeding artery and large communication with venous sac.
F, Angiogram after embolization, obtained with coils introduced through lumen of balloon catheter during balloon inflation, shows successful occlusion.

migration of thrombi that form on these coils into the draining pulmonary vein and thence into the systemic circulation. In addition, the resulting "coil ball" will remain indefinitely, whereas in a pulmonary arteriovenous malformation treated by conventional coil occlusion, the sac will usually disappear (Fig. 3).

Use of an occlusion balloon.—In two patients with especially large pulmonary arteriovenous malformations through which the flow was extremely rapid, an occlusion balloon was inflated in the feeding vessel to control flow during coil deployment, which was performed through the lumen of the occlusion balloon catheter (Fig. 3). This technique is useful when a stable catheter position at a site appropriate for embolization in large feeding vessels cannot be achieved with a conventional catheter. The two lesions treated in this manner had feeding vessels of 7 and 9 mm in diameter.

Coil Migration

A single potentially serious complication occurred when a coil that was too small for the vessel being embolized migrated through a pulmonary arteriovenous malformation into the systemic circulation and lodged in the left popliteal artery, from which it was successfully retrieved. Coil migration has not occurred again from the time that we began using detachable coils routinely. Coil migration remains a possible complication that is discussed with all patients before the procedure. In the worst scenario, the coil migrates into the cerebral vessels and causes cerebrovascular ischemia and perhaps infarction. We know of only one instance of coil migration to an internal carotid artery, from which it was successfully retrieved without complication (White R, personal communication).

Gas Exchange

Successive series from our institution [16, 18] and others [15, 17, 19] have shown a decrease in the right-to-left shunt both before and after embolization. A similar improvement was noted in all indexes of oxygenation (Sa_{O_2}) and, in a subgroup of patients with impaired gas transfer, improvement in KCO. The probable reason for the higher Sa_{O_2} and lower right-to-left shunt before embolization in more recent series is that family screening procedures and better awareness of hereditary hemorrhagic telangiectasia and its complications by patients, their families, and physicians, mean that patients are now presenting at a less symptomatic stage and before serious complications occur. Tables 3–5 summarize the physiologic data in terms of oxygenation, right-to-left shunt, and exercise capacity for three categories of patients: group 1, patients with complete occlusion of all angiographically visible pulmonary arteriovenous malformations; group 2, patients with residual shunts remaining in pulmonary arteriovenous malformations with feeding vessels too small for embolization therapy (<3 mm in diameter); and group 3, patients whose treatment was incomplete and in whom pulmonary arteriovenous malformations with feeders greater than 3 mm remain. The mean shunt after embolization was least in group 1 (7%), intermediate in group 2 (10%), and greatest in group 3 (19%). Tables 3–5 also show a similar trend among groups in all indexes of oxygenation. Interestingly, in group 1, whose treatment was angiographically complete, the anatomic right-to-left shunt remained abnormal by our standards [37] at greater than 3.5% in two (11%) of 18 patients, implying (in the absence of a patent foramen ovale) that pulmonary arteriovenous malformations beyond the resolution of angiography must have been present.

Exercise Outcomes

Most patients subjectively report an improvement after embolization in exercise capacity in terms of daily living [15], a finding with which we agree; an objective increase in exercise capacity (increase in the oxygen uptake at maximal exercise [$V_{O_{2(max)}}$]) has also been reported in a small number of patients [17]. In this series, and in two previous reports from our hospital, we found that an objective increase in exercise capacity occurs in only a minority of patients after embolization (6/14 [23], 15/41 [18], and 10/46 in this study). This finding has two probable reasons. First, the exercise protocol, generally an increase in workload of 30 W/min, is a somewhat blunt tool that may overlook subtle but small improvements. Second, patients with pulmonary arteriovenous malformations have efficiently adapted to delivering oxygen to muscles that are exercising (polycythemia and a supranormal cardiac output) [38], so that their exercise capacity before embolization may not be markedly impaired.

Pulmonary Function

In the absence of pulmonary infarction and scarring, no reason exists for the FEV_1 and vital capacity to change after embolization; this has been the case in this and other series. Because DLCO and KCO reflect the function of the pulmonary microcirculation, they might not be expected to be affected by embolization of large pulmonary arteriovenous malformations. In two other series [17, 23], the researchers did not find any significant increase in DLCO or KCO except in a subgroup of four patients with pulmonary arteriovenous malformations that were not associated with hereditary hemorrhagic telangiectasia [17]. On the other hand, we showed in another series of patients that a small (1.3%) insignificant increase in DLCO and a small but significant increase in KCO (5.2%; $p = 0.02$) occurred after embolization [18]. Most patients in our study had DLCO and KCO within the normal range before embolization, and we specifically analyzed the subgroup (16/60) whose KCO before embolization was less than 90% of the predicted value. In that group, we found a significant improvement in KCO, from 77.5% to 86.8%.

The subgroup with improved KCO does not correspond to the subgroup with improved exercise capacity. Of the patients in whom exercise capacity improved, only three of 13 had KCO of less than 90% of the predicted value. Conversely, exercise tolerance increased in only three of 13 patients with KCO of less than 90% for whom full exercise measurements were available, and only one of these had an increase in KCO as a result of the procedure. Therefore, the improvements in exercise tolerance and in DLCO in subgroups of patients appear to be independent. In general, impaired gas transfer is associated with impaired exercise capacity, so this finding is a little surprising and indicates the extent to which additional factors such as hemodynamics may influence exercise capacity.

Conclusion

Coil embolization of pulmonary arteriovenous malformations is a well-tolerated procedure with a low complication rate and is effective in terms of reduction in right-to-left anatomic shunt fraction and improvement in arterial oxygenation. Although most patients report a subjective improvement in exercise tolerance after treatment, an objective improvement is difficult to show. In individuals with a KCO of less than 90% of the predicted value, a significant improvement of this measurement can be expected after embolization.

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