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Pulmonary Artery Hemodynamics in Primary Pulmonary Hypertension

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Objectives. **The present investigation compared and contrasted steady and pulsatile pulmonary hemodynamics at rest and during exercise in patients with primary pulmonary hypertension and normal control subjects.**

Background. **A complete description of the relation between pressure and flow in the pulmonary circulation includes both steady and pulsatile hemodynamic behavior. Patients with primary pulmonary hypertension provide a unique opportunity to study the effects of primary alterations in pulmonary vasculature on pulmonary artery vascular hydraulic load.**

Methods. **Catheter tip pressure and velocity recordings from the main pulmonary artery in 8 patients with primary pulmonary hypertension and 10 control subjects were used to derive the pulmonary artery input impedance spectrum and the extent of pulse wave reflection at rest and during exercise.**

Results. **As expected, in patients with primary pulmonary hypertension, mean pulmonary artery pressure (50 ± 10 mm Hg) and pulmonary vascular resistance (880 ± 446 dynes·s·cm^{-5}) were markedly elevated at rest and remained so during exercise (mean pressure 71 ± 15 mm Hg, mean resistance 750 ± 530 dynes·s·cm^{-5}). Pulmonary artery characteristic impedance was elevated at rest and did not change with exercise (rest 55 ± 25 dynes·s·cm^{-5}; exercise 66 ± 33 dynes·s·cm^{-5}). Measures of arterial wave reflection indicated that the extent of wave reflection in the pulmonary bed in those with primary pulmonary hypertension is large at rest (reflection coefficient 0.89 ± 0.09) and that the composite reflected wave arrived during the midportion of right ventricular ejection. Although the extent of wave reflection decreased with exercise (reflection coefficient 0.81 ± 0.10, $p < 0.05$), the magnitude and timing of these reflections remained adverse. Furthermore, in patients with primary pulmonary hypertension, the stroke volume response to exercise was strongly related to rest levels of pulmonary artery diastolic pressure, pulmonary vascular resistance and the reflection factor, whereas no such relation was found in the control subjects.**

Conclusions. **In addition to the expected abnormalities in steady measures of pulmonary artery hemodynamics at rest in patients with primary pulmonary hypertension, rest and exercise measures of oscillatory behavior (characteristic impedance and pulse wave reflection) are perturbed. Measures of steady and pulsatile behavior, particularly wave reflection, appear to have an important role in the exercise response of these patients.**

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Primary pulmonary hypertension is an inexorable obliterative disease of the pulmonary vasculature and results in marked elevations of pulmonary artery pressure and pulmonary vascular resistance at rest (1–5). The development of exercise intolerance in patients with primary pulmonary hypertension indicates an alteration in the pulmonary pressure-flow relation notwithstanding a relatively preserved cardiac output at rest (1). Only a few studies (6–8) have described pulsatile hemodynamic behavior in the pulmonary circulation in patients with pulmonary hypertension and, to our knowledge, no studies are available describing the steady and pulsatile response of the pulmonary circulation to exercise in patients with pulmonary hypertension.

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Chronic pulmonary hypertension of any origin frequently results in pathologic changes in the proximal (elastic) and distal (resistive) pulmonary vasculature. The opposition to both steady and pulsatile flow, or vascular hydraulic load, can be represented by the pulmonary artery input impedance spectrum. This frequency-dependent function encompasses information about the resistive, capacitive and inertial components of vascular hydraulic load, as well as the extent of pulse wave reflection.

The purpose of the present study, therefore, was to compare and contrast the hydraulic vascular load in the pulmonary circulation at rest and during supine exercise in patients with primary pulmonary hypertension and normal control subjects. It was our hypothesis that the exercise response in primary pulmonary hypertension would be significantly different from normal and that both mean and pulsatile behavior would be importantly related to the exercise response.

Methods

Study patients. Ten patients undergoing diagnostic cardiac catheterization were found free of detectable cardiovas-

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cular disease. There were seven men and three women aged 34 to 58 years (mean 46 ± 16). This group served as the normal control group.

Fourteen patients at our institution believed to be suitable candidates for an ongoing investigation of the effects of vasodilator therapy in primary pulmonary hypertension were referred to the cardiac catheterization laboratory from 1983 to 1989 to rule out secondary causes of pulmonary hypertension. Technical difficulties predominantly related to vascular access precluded full catheter instrumentation in six of these patients. Therefore, a total of eight patients participated in the investigational protocol. There were three men and five women aged 18 to 63 years (mean 45 ± 17). No patient was receiving oral vasodilators at the time of this examination. No patient was demonstrated to have an identifiable (secondary) cause of pulmonary hypertension and, therefore, these eight patients fulfilled criteria for the diagnosis of primary pulmonary hypertension (1,4,7). All patients gave written consent in accord with guidelines established by the University of Pennsylvania Committee on Studies Involving Human Beings.

Experimental protocol. Hemodynamic studies were conducted in the fasting state before radiocontrast administration. An 8F multisensor catheter tip-manometer (VPC684D, Millar Instruments) was advanced to the pulmonary artery under fluoroscopic guidance by means of a right brachial venotomy. A thermodilution Swan-Ganz catheter was advanced to the pulmonary artery through a separate right brachial vein. Cuff blood pressure was obtained from the left brachial artery. Measurements at rest were obtained with the subject's feet passively elevated in the pedals of a table-mounted bicycle ergometer. This condition was used as the control state for all exercise comparisons. Pulmonary artery pressure and velocity signals at rest were obtained continuously for 2 min. Thermodilution cardiac output measurements were obtained on three to five occasions over this interval and averaged. After the establishment of steady state conditions (that is, unchanging pulmonary artery pressure and oxygen saturation), the subject was instructed to begin bicycle exercise at an external work load of 25 W for at least 3-min duration. Steady state levels at exercise were confirmed by unchanging consecutive pulmonary artery oxygen saturation measurements. Pressure and velocity signals were recorded continuously over the last minute of exercise and thermodilution cardiac output was again obtained during this interval.

All exercise protocols were successfully completed without complications or patient intolerance (other than dyspnea). No subject experienced a decrease in systemic arterial blood pressure during exercise. At the completion of the exercise portion of the procedure, the remaining portion of the diagnostic catheterization was completed.

Data acquisition and analysis. Our methods for high fidelity catheter instrumentation and recording have been previously reported (9,10). A 500-Hz square wave electromagnetic flow meter (Carolina Medical Instruments, model 501) was used to drive the catheter-mounted electromagnetic probe and was operated at the 100-Hz filter setting. The output velocity signal was subsequently scaled to the simultaneously determined thermodilution cardiac output for both rest and exercise conditions. This assumes a circular geometry and a flat velocity profile at the proximal pulmonary artery under both rest and exercise conditions. Notably, no patient had clinically detectable triscupid regurgitation or a mean right atrial pressure >10 mm Hg in the rest state. To ensure equisensitivity of the pulmonary artery and right ventricular sensors, after electrical zeroing and calibration, the catheter was advanced to the distal pulmonary artery so that pulmonary artery (distal) and right ventricular (proximal) sensors were both recording the pulmonary artery pressure. Each high fidelity pressure signal was then aligned with the simultaneously obtained pulmonary artery pressure from the fluid-filled catheter system. The multisensor catheter was then slightly withdrawn so that pulmonary artery and right ventricular pressures were redisplayed.

For each physiologic state, a minimum of 1 min of continuous data was recorded on a Hewlett-Packard FM tape recorder. Data were subsequently digitized at 4-ms intervals using a 12-bit analog to digital converter that incorporated a 50-Hz low pass filter. Beats were selected for analysis if they were free of obvious distortion or artifact and did not follow a premature contraction. In this manner, 20 to 40 selected beats, encompassing several respiratory cycles, were signal averaged in the time domain. We (11) and others (12) have previously shown that there is no significant respiratory variation in impedance spectra either at rest or during exercise. Resolution of the pulmonary artery pressure and flow into their respective Fourier series was accomplished as previously described (10). The noise level for this system, determined from in vitro recording, was set at 0.1 mm Hg for pressure and 5 ml/s for flow. These values represent the threshold below which harmonics were rejected. Pulmonary artery input impedance moduli and phase were then calculated. Pulmonary artery characteristic impedance was taken as the average of impedance moduli at frequencies >2 Hz. The frequency at which the first impedance minimum occurred was noted. Time and frequency domain measures of the extent of wave reflection were calculated as previously described (13–15).

Pulmonary vascular resistance was derived from the difference in mean pulmonary artery and pulmonary capillary wedge pressure divided by the cardiac output. The direct current (DC) term of the pulmonary artery impedance spectrum (pulmonary input resistance) correlated well with the pulmonary vascular resistance ($r = 0.98$, $p < 0.001$) but was not further used in the reporting of results.

Statistical analysis. All data are expressed as mean value ± SD. Rest and exercise variables were compared with a paired t test. Intergroup comparisons were accomplished using a two-way analysis of variance. Because of the small sample size, we report all p values. Statistical significance was defined when $p \leq 0.05$. Stepwise multiple regres-

Table 1. Control Group: Steady Hemodynamics at Rest and During Exercise

Pt No.	Age (yr)/ Gender	PAP (S/D/mean)		CO		PVR	
		R	Ex	R	Ex	R	Ex
1	49/F	22/9/13	26/14/18	5.0	8.0	54	67
2	51/M	16/8/11	24/12/16	6.7	10.2	87	66
3	34/M	24/19/20	23/17/19	9.6	14.4	106	57
4	40/M	26/11/16	33/15/21	6.8	14.8	38	49
5	45/M	26/11/16	24/8/13	8.1	13.6	109	50
6	41/F	18/5/9	24/5/11	8.5	16.4	24	57
7	53/M	25/10/15	24/9/14	6.2	10.5	96	65
8	47/M	30/13/19	45/19/28	8.8	13.2	101	123
9	38/F	21/8/12	21/9/13	5.7	10.9	79	60
10	58/M	27/12/17	36/16/23	8.5	12.4	37	107
Mean	46	23/10/14	28/12/17	7.4	12.4	73	70
± SD	16	4/4/5	8/4/7	1.5	2.5	32	25
p value (R vs. Ex)		0.03/0.10/0.07		0.001		0.8	

CO = cardiac output (liters/min); D = diastolic; Ex = exercise; F = female; M = male; PAP = pulmonary artery pressure (mm Hg); Pt = patient; PVR = pulmonary vascular resistance (dynes·s·cm^{-5}); R = rest; S = systolic.

sion using selected steady and pulsatile measures at rest was accomplished by using a forward stepwise technique with default entry criteria (Abacus Concepts, Statview II).

Results

Steady hemodynamics. Table 1 outlines the steady pulmonary hemodynamic values at rest and during exercise in the 10 normal control subjects. Statistically significant increases in cardiac output were mediated by significant increases in both heart rate and stroke volume (rest 106 ± 17 ml; exercise 128 ± 33 ml; p = 0.007). There was no significant change in pulmonary artery mean or diastolic pressure during exercise; pulmonary vascular resistance also was unchanged. In addition, pulmonary capillary wedge pressure at rest (9 ± 3 mm Hg) did not change with exercise.

Table 2 outlines the steady pulmonary hemodynamics at rest in all eight patients with primary pulmonary hypertension and during exercise in seven. One patient (Patient 6) was deemed hemodynamically unstable and therefore did not complete the exercise protocol. As expected, pulmonary artery pressures and pulmonary vascular resistance were uniformly elevated. The group mean cardiac output at rest was only slightly depressed compared with normal values. The transition from rest to exercise was notable for a significant increase in pulmonary artery pressure and no significant change in pulmonary vascular resistance. Although there was a significant increase in cardiac output during exercise, this increase was achieved as the result of an exercise-related increase in heart rate with overall stroke volume unchanged (mean stroke volume 57 ± 24 ml at rest, 67 ± 34 ml during exercise, p = 0.13). There was no significant change in pulmonary capillary wedge pressure from rest (8 ± 4 mm Hg) to exercise (12 ± 8 mm Hg, p = 0.09).

Pulsatile hemodynamics. Table 3 outlines the pulsatile hemodynamic values in normal control subjects at rest and during exercise. There was no significant change in pulmonary artery characteristic impedance during exercise. The decrease in modulus of the first harmonic of impedance

Table 2. Patient Group: Steady Hemodynamics at Rest and During Exercise

Pt No.	Age (yr)/ Gender	PAP (S/D/mean)		CO		PVR	
		R	Ex	R	Ex	R	Ex
1	62/M	61/18/35	91/30/54	6.2	10.5	219	198
2	36/M	63/24/41	91/35/58	3.8	6.6	779	582
3	63/F	85/28/50	101/34/62	7.5	10.0	427	384
4	18/F	62/30/42	98/49/69	4.0	7.2	680	456
5	49/F	87/30/50	155/60/98	2.4	3.9	1,400	1,764
6	63/M	112/43/67	—	3.3	—	1,479	—
7	28/F	95/38/60	114/44/76	4.9	7.0	898	800
8	45/F	86/38/56	116/48/77	3.6	5.6	1,156	1,071
Mean	45	81/31/50	109/43/71	4.5	7.3	880	750
± SD	17	18/8/10	22/10/15	1.7	2.3	446	530
p value (R vs. Ex)		0.002/0.006/0.002		0.003		0.6	

Abbreviations as in Table 1.

Table 3. Pulsatile Pulmonary Artery Hemodynamics in Control Subjects

	Zc		Z1		fmin (Hz)		BWAT		RF		Γ1	
Pt No.	R	Ex	R	Ex	R	Ex	R	Ex	R	Ex	R	Ex
1	25	51	44	36	1.8	2.9	0.61	1.09	0.21	0.45	0.38	0.40
2	15	22	20	19	3.7	1.7	1.27	1.33	0.24	0.22	0.42	0.34
3	8	12	11	10	4.1	3.3	0.84	1.03	0.19	0.10	0.22	0.13
4	19	22	52	34	3.8	4.6	0.71	1.09	0.42	0.24	0.48	0.24
5	14	11	42	31	3.0	6.3	0.67	0.52	0.46	0.46	0.61	0.57
6	24	21	30	21	3.7	3.2	0.87	0.77	0.23	0.32	0.34	0.44
7	29	32	45	32	3.5	3.5	1.10	1.04	0.27	0.19	0.27	0.15
8	19	21	39	50	5.1	5.3	0.71	0.54	0.48	0.53	0.57	0.55
9	47	29	58	23	3.1	1.9	0.14	1.26	0.22	0.27	0.24	0.20
10	21	34	38	38	4.4	3.7	0.71	1.08	0.54	0.28	0.59	0.28
Mean	22	26	38	29	3.6	3.7	0.86	0.98	0.33	0.31	0.41	0.33
± SD	11	12	14	11	0.9	1.6	0.23	0.28	0.13	0.13	0.15	0.16
p value (R vs. Ex)	0.4		0.06		0.9		0.17		0.7		0.06	

BWAT = backward wave time/right ventricular ejection time ratio; fmin = frequency at first impedance minimum; RF = reflection factor; Zc = characteristic impedance; Z1 = value of first harmonic impedance modulus; Γ1 = coefficient of wave reflection for first harmonic; other abbreviations as in Table 1.

failed to reach statistical significance. No significant change during exercise was noted in the time domain reflection factor. Exercise resulted in no significant change in the frequency at which the impedance spectrum exhibited a first minimum (fmin) or in the backward wave arrival time at the pulmonary inlet. Taken together, these findings indicate no significant change in pulse wave velocity or location of a major reflection site.

Table 4 outlines the pulsatile pulmonary hemodynamic behavior of the patients with primary pulmonary hypertension. Pulmonary artery characteristic impedance at rest was elevated compared with normal values and did not change during exercise. The elevated modulus of the first harmonic of impedance also remained unchanged during exercise. The modulus of the first harmonic of the complex reflection coefficient at rest was significantly increased compared with normal values but decreased with exercise. This trend was also seen in the time domain reflection factor, although the decrease was not statistically significant. There was a pronounced and significant rightward shift in the frequency at which the input impedance spectrum exhibited a first minimum. This finding is consistent with an increase in pulse wave velocity or a shift in the location of the major reflection site, or both. In support of the latter observation was a decrease in the backward, or reflected, wave arrival time at the pulmonary inlet (rest 311 ± 11 ms; exercise 240 ± 22 ms; $p < 0.001$). Moreover, the location of the peak of this reflected wave within the interval of right ventricular ejection indicated that the reflected wave arrived even earlier during exercise (Fig. 1).

Table 5 summarizes the important differences in pulsatile pulmonary artery hemodynamics between patients with primary pulmonary hypertension and the normal control subjects. Pulmonary artery stiffness is represented by the characteristic impedance; wave velocity is represented by the frequency at first impedance minimum and backward wave arrival time; reflection properties are represented by the reflection factor.

Although there was no significant overall stroke volume response to exercise in patients with primary pulmonary

Table 4. Pulsatile Pulmonary Artery Hemodynamics in Patients With Primary Pulmonary Hypertension

	Zc		Z1		fmin (Hz)		BWAT		RF		Γ1	
Pt No.	R	Ex	R	Ex	R	Ex	R	Ex	R	Ex	R	Ex
1	38	38	197	213	5.0	9.3	0.58	0.46	0.67	0.70	0.88	0.88
2	19	35	173	245	4.0	5.4	0.70	0.66	0.90	0.96	0.97	0.94
3	95	80	250	228	4.2	7.0	0.67	0.63	0.65	0.58	0.72	0.67
4	60	41	218	169	6.2	9.7	0.78	0.72	0.76	0.72	0.78	0.69
5	79	128	766	882	6.3	7.5	0.65	0.61	1.12	0.93	0.96	0.79
6	54	—	758	—	6.9	—	0.64	—	1.05	—	0.98	—
7	44	60	459	269	5.6	10.4	0.73	0.66	0.89	0.79	0.90	0.88
8	49	84	261	279	4.6	6.8	0.68	0.60	1.0	0.89	0.95	0.84
Mean	54.7	66.5	385	326	5.3	8.0	0.68	0.62	0.88	0.80	0.89	0.81
± SD	25	33	213	247	0.9	1.8	0.06	0.08	0.17	0.14	0.09	0.10
p value (R vs. Ex)	0.27		0.9		0.001		0.002		0.10		0.02	

Abbreviations as in Tables 1 and 3.

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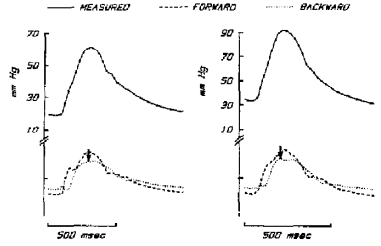

Figure 1. Pulmonary artery pressure at rest (left) and during exercise (right). The measured wave is decomposed into a composite anterograde and reflected wave. The peak of the reflected wave at rest occurs well within the interval of ejection and arrives even earlier during exercise.

hypertension, there was substantial individual variation. On stepwise multiple regression using six measures of rest steady and pulsatile vascular load (pulmonary artery systolic, diastolic and mean pressure, pulmonary vascular resistance, first harmonic of impedance and reflection factor), predictors of the exercise stroke volume response were pulmonary artery diastolic pressure (inversely), pulmonary vascular resistance (inversely) and the reflection factor (direct). The overall r^2 for the model was 0.98. No such relation could be demonstrated in the normal control group.

Discussion

In this report, we demonstrate that alterations in pulmonary artery vascular hydraulic load are present in the rest state in patients with primary pulmonary hypertension and that these abnormalities persist during exercise. These findings indicate that in these patients, proximal pulmonary artery distensibility (characteristic impedance) is decreased, measures of pulse wave reflection and velocity are increased and both steady and pulsatile components of the pulmonary artery vascular hydraulic load have considerable impact on the exercise response.

Table 5. Rest and Exercise Pulmonary Artery Properties in Patients With Primary Pulmonary Hypertension Compared With Values in Normal Control Subjects

PA Stiffness		Wave Velocity		Reflections	
R	Ex	R	Ex	R	Ex
↑*	↑*	↑*	↑*↑†	↑*	↑*↓†

*$p < 0.01$ versus normal control subjects. †$p < 0.01$ versus rest. PA = pulmonary artery; ↑ = increased; ↓ = decreased; other abbreviations as in Table 1.

Alterations in pulmonary artery characteristic impedance. Pulmonary hypertension secondary to diverse etiologies, both clinically and experimentally, has been characterized by an elevated pulmonary artery characteristic impedance (6,7,16–18), although several studies (17,19) have also reported an unaltered characteristic impedance. The characteristic impedance of a vessel is dependent on both the distensibility, or "compliance," and geometry of that vessel. In addition, characteristic impedance varies directly with the complex wave velocity. Therefore, it is notable that in virtually all experimental and clinical studies of pulmonary hypertension, evidence for an increase in pulse wave velocity has been detected. In human disease states, an elevated pulmonary artery characteristic impedance has been noted in mitral valve stenosis (6,7), congestive heart failure (20) and intracardiac shunts (21). These results are supported by several studies (22,23) reporting concordant alterations in pulmonary artery compliance.

Alterations in indexes of pulmonary artery wave reflection. In the present study, we noted striking elevations in indexes of pulmonary artery wave reflection both at rest and during exercise. In normal subjects, there was an inconsistent trend toward a decrease in the extent of wave reflection during exercise. This trend was also observed in our patients with primary pulmonary hypertension, although exercise levels remained elevated in comparison with those in normal subjects. This is of interest in view of the failure of pulmonary vascular resistance to significantly decrease during exercise. Because the same phenomenon (that is, a decrease in the extent of wave reflection in the absence of a significant decrease in pulmonary vascular resistance) was observed in normal subjects, a common mechanism may be operant. It has traditionally been assumed that the vast majority of arterial wave reflection occurs in the periphery or at the termination of the arterial bed. Thus, peripheral vasoconstriction leads to augmented wave reflection and peripheral vasodilation to diminished wave reflection (24). Recently, however, diminished wave reflection has been demonstrated in the absence of peripheral vasodilation (25). These latter data obtained in the systemic arterial circulation and our data obtained in the pulmonary circulation suggest an additional site of wave reflection that effectively "uncouples" the central and peripheral vasculature.

The timing of the arrival of the backward wave (which is additive to the incident pressure wave but subtracts from the incident flow wave) is adverse and remains so during exercise. In fact, the backward wave arrived earlier during ejection in these patients with primary pulmonary hypertension than in normal subjects (unpublished observations). Furthermore, as can be seen from inspection of the pressure pulse in Figure 1, the backward wave arrives at a time when an important fraction of forward flow is still occurring. This is all the more important in view of the length of available time that forward flow occurs. The same reasoning can be applied to pressure-related events. In this instance, because pressure peaks later than flow, the arrival of a reflected

pressure wave is likely to occur at a time when pressure is still increasing, thereby resulting in a deleterious increase in impedance modulus. This may explain the failure of the first harmonic impedance to decrease during exercise.

Interrelation between steady and pulsatile hemodynamic behavior. This relation is not easily analyzed or expressed. This is the result of the independence of frequency domain terms from the steady, or DC, term. However, the importance of pulsatile hemodynamics (for example, wave travel and reflection) to overall circulatory function can be seen in the relation between steady and pulsatile measures of the load and the (variable) change in stroke volume with exercise. The strongest correlates of the exercise stroke volume response in primary pulmonary hypertension were rest levels of pulmonary artery diastolic pressure and pulmonary vascular resistance (components of the steady portion of the load) and the reflection factor (a component of the pulsatile portion of the load). This relation underscores the importance of considering the total vascular hydraulic load encountered by the ejecting right ventricle.

Limitations of the study. Methodologic and technical limitations caution against generalizing these findings to all patients with primary pulmonary hypertension. Our study patients were referred for catheterization because of the strong clinical suspicion of primary pulmonary hypertension. The failure to observe more significant changes in mean and pulsatile behavior during exercise may be in part related to the small sample size. The increased prevalence of female patients with primary pulmonary hypertension presents additional difficulties. Although we attempted to age match the study groups, the gender mix was imbalanced. We are unaware of any data indicating gender-based differences in pulmonary hemodynamics, although it is possible that they exist. The derivation of pulmonary artery characteristic impedance is imprecise. The latter is reported in terms of volume flow rather than linear velocity. The acquisition of simultaneously determined cardiac output measurements and the concordance of our mean value for characteristic impedance with the limited published data available (6–8) tend to support these methods. The absence of clinical and hemodynamic evidence for tricuspid regurgitation at rest allows for assessment of cardiac output by thermodilution technique. We cannot exclude the possibility that tricupid regurgitation may have occurred during exercise and thereby may have affected subsequent calculations.

The assumptions and limitations of the derivation of the pulmonary artery input impedance spectrum have been previously defended (6). It is acknowledged that in the absence of dimensional data or characterization of the velocity profile in the main pulmonary artery in patients with primary pulmonary hypertension, catheter tip velocity recordings may not be representative or adequate for application in the present manner. Images obtained from intravascular ultrasound of the main pulmonary artery have clearly demonstrated a circular cross section and should allay concerns about nonlinear elements resulting from noncircular geometry of the proximal pulmonary artery (26). Blunt velocity profiles at the pulmonary inlet have been described (27). Other imaging techniques such as fast computed tomographic scanning may be useful in this regard, although the task of obtaining simultaneous exercise hemodynamics is formidable.

Conclusions. We observed significant increases in the steady and pulsatile components of the pulmonary vascular hydraulic load in patients with primary pulmonary hypertension. These alterations persisted during exercise and contrast strongly with normal pulmonary hemodynamic behavior. In addition, abnormalities in pulse wave propagation and reflection contributed significantly to the abnormal exercise response in these subjects. The merit of pharmacologic manipulation of both steady and pulsatile behavior has been demonstrated in the systemic arterial circulation. The possibility of beneficially altering pulse wave propagation and reflection in the pulmonary bed with vasodilators awaits further study.

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