Mesenteric Blood Flow Response to Feeding After Systemic-to-Pulmonary Arterial Shunt Palliation

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Background. **We hypothesized that the splanchnic circulation protects against diastolic steal through a systemic-to-pulmonary arterial shunt by reducing its resistance. To test the hypothesis we compared the basal and postprandial mesenteric blood flow velocities and vascular resistance in infants after shunt palliation for their underlying cyanotic heart disease with those in nonshunted infants.**

Methods. **The basal and postprandial superior mesenteric arterial (SMA) time-average flow velocity (TAMV), end-diastolic flow velocity (EDFV), and relative resistance were assessed in 23 infants with congenital heart disease. The findings in the 9 shunted infants (group I) were compared with those in 14 nonshunted ones (group II).**

Results. **In group II, TAMV (0.25 ± 0.07 versus 0.33 ± 0.09 m/s, $p < 0.001$) and EDFV (0.08 ± 0.04 versus 0.11 ± 0.04 m/s, $p = 0.003$) increased, while SMA relative resistance decreased (297 ± 121 versus 198 ± 73 mm Hg/ms^{-1}, $p < 0.001$) postprandially. Similarly, in group I, TAMV (0.35 ± 0.13 versus 0.48 ± 0.19 m/s, $p = 0.008$) increased, while SMA relative resistance decreased (182 ± 61 versus 116 ± 38 mm Hg/ms^{-1}, $p = 0.005$) after feeding. However, whereas basal and postprandial diastolic flow was antegrade in group II, absent or retrograde diastolic flow was characteristic of group I (preprandial, −0.10 ± 0.07 m/s; postprandial, −0.13 ± 0.06 m/s). Furthermore, group I had significantly lower SMA relative resistance both before ($p = 0.02$) and after ($p = 0.006$) feeding.**

Conclusions. **Profound disturbance of splanchnic perfusion occurs in infants palliated with a systemic-to-pulmonary arterial shunt. Their basal and postprandial SMA diastolic blood flow is either absent or reversed. The lowering of basal and postprandial resistance of the splanchnic circulation probably represents an adaptive mechanism to counteract such diastolic steal.**

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The initial palliative surgery for infants with duct-dependent cyanotic heart disease is insertion of a systemic-to-pulmonary arterial shunt, which serves a similar function as a patent ductus arteriosus hemodynamically. A large patent ductus arteriosus has been shown to cause profound disturbance in mid-gut perfusion, resulting in absent or reverse diastolic flow in the superior mesenteric artery [1]. Such diastolic steal from the descending aorta is thought to contribute to intestinal ischemia [2], which may explain in part the increased risk of necrotizing enterocolitis in infants with cyanotic congenital heart disease and a large patent ductus arteriosus [3]. There are, however, no data to support that systemic-to-pulmonary arterial shunt insertion confers a similar risk. While the effect of patent ductus arteriosus on splanchnic blood flow has been well documented [1], the impact of systemic-to-pulmonary arterial shunt palliation on mesenteric blood flow is unknown.

Superior mesenteric arterial (SMA) blood flow can readily be assessed by Doppler ultrasonography [4]. It has been shown that enteral feeding induces a significant increase in blood flow velocity in SMA that peaks 30 to 45 minutes after the feed [4, 5]. Enteral feeding may thus help to unmask even subtle alterations in splanchnic perfusion, if indeed it is present. We hypothesized that while the splanchnic perfusion may be disturbed in young infants after palliative systemic-pulmonary arterial shunt operation due to the diastolic steal phenomenon, the splanchnic circulation protects by reducing its vascular resistance. To test the hypothesis we compared the basal and postprandial SMA blood flow velocities and relative mesenteric vascular resistance in infants who had undergone shunt insertion for their underlying cyanotic congenital heart disease with that in nonshunted patients.

Patients and Methods

Patients

Twenty-three infants with congenital heart disease were studied at a median age of 54 days (range 5 to 122) and median weight of 3.9 kg (range 2.1 to 4.6). The patients were categorized into two groups for comparison. Group I comprised patients with cyanotic congenital heart disease who had undergone insertion of a systemic-pulmonary arterial shunt. Group II comprised infants whose arterial ducts had closed with either non–ductal-dependent cyanotic heart diseases or acyanotic heart

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Table 1. Demographic and Clinical Data of the Patients

Variables	Group I (n = 9)	Group II (n = 14)	*p* Value
Median age (range) (days)	34 (12–15)	73 (5–122)	0.83
Median weight (range) (kg)	3.6 (2.1–6.4)	4.0 (2.2–5.3)	0.31
Median systemic oxygen saturation (range) (%)	85 (81–98)	98 (70–100)	0.12
Cardiac diagnosis	PAIVS (n = 4)	Acyanotic	
	PAVSD (n = 2)	VSD	(n = 3)
	severe TOF (n = 2)	Valvar PS	(n = 3)
	DORV, PS (n = 1)	TGA, post ASO	(n = 2)
		CoA post repair	(n = 1)
		VSD post repair	(n = 1)
		Cyanotic	
		TGA, VSD	(n = 1)
		TOF	(n = 1)
		Right atrial isomerism, DOIV, PS	(n = 1)
		Critical PS post balloon valvoplasty	(n = 1)

ASO = arterial switch operation; CoA = coarctation of aorta; DOIV = double-inlet indeterminate ventricle; DORV = double-outlet right ventricle; PAIVS = pulmonary atresia with intact ventricular septum; PAVSD = pulmonary atresia with ventricular septal defect; PS = pulmonary stenosis; TGA = transposition of great arteries; TOF = tetralogy of Fallot; VSD = ventricular septal defect.

lesions. Their cardiac diagnoses are summarized in Table 1.

In all of the infants the following variables were assessed immediately before milk feed and 30 minutes afterwards: pulse oximetry reading, systemic blood pressure, SMA time-averaged mean velocity (TAMV), end-diastolic flow velocity (EDFV), area under peak velocity envelope (AUPVE), SMA relative vascular resistance, and systemic cardiac output. The systemic blood pressure was measured by an automatic oscillometric device (Dinamap [Critikon, Tampa, FL]), while the SMA flow dynamics and cardiac output were derived by echocardiographic and Doppler assessments.

Measurement of SMA Flow Dynamics

Doppler examination of the SMA blood flow was performed by a single person using a phased-array transducer (fusion imaging frequency 7 to 12 MHz) interfaced to a Hewlett-Packard Sonos 5500 ultrasound machine (Hewlett-Packard, Andover, MA). Measurements of the SMA flow velocities and resistance were obtained as previously described [4–6]. The nonsedated infants were examined in a supine position with the transducer positioned in midabdomen above the umbilicus in the sagittal plane. The SMA was localized using color flow mapping. The sample volume was placed within 2 to 3 mm distal from its branching point from the descending aorta, with an angle of insonation of less than 15 degrees. From the peak velocity envelope of the velocity spectrum the mean of two separate readings of TAMV, EDFV and AUPVE, each derived from averaging the measurements from three consecutive cardiac cycles, was calculated. The SMA relative vascular resistance was derived from the formula: mean blood pressure divided by TAMV. The median coefficient of variation of preprandial SMA velocities and AUPVE at difference times has been reported to vary between 7% and 15% [5].

Cardiac Output

The total cardiac output was estimated from the aortic flow velocity and aortic diameter. The ascending aorta was studied from the high left parasternal or suprasternal location. The sample volume of the pulse Doppler was placed at the level of aortic valve orifice and the aortic diameter was measured during systole. From the velocity envelope the area under the curve (AUC) per cardiac cycle was measured. The cardiac output normalized to body weight was derived from the following formula:

$$[\pi(\text{diameter}/2)^2 \times \text{AUC} \times \text{heart rate}/\text{body weight}].$$

Data Analysis

All data are presented as mean ± SD unless otherwise stated. The paired Student's *t* test was used to compare preprandial and postprandial hemodynamic variables and the unpaired Student's *t* test was used for intergroup comparisons. Comparison of the nonparametric demographic data between the two groups was performed using Mann Whitney *U* test. All of the *p* values are presented and no correction was made for the multiple tests. A *p* value of less than 0.05 was considered statistically significant. All statistical analyses were performed using SPSS version 7.5 (SPSS, Chicago, IL).

Results

Patients

Group I comprised 9 infants who were studied at a median of 18 days (range 4 to 124) after insertion of a modified Blalock-Taussig shunt. All patients but 1 had a 4-mm shunt inserted whereas the other patient had a 3.5-mm shunt. Group II comprised 14 infants with either acyanotic congenital heart disease or non–shunt-

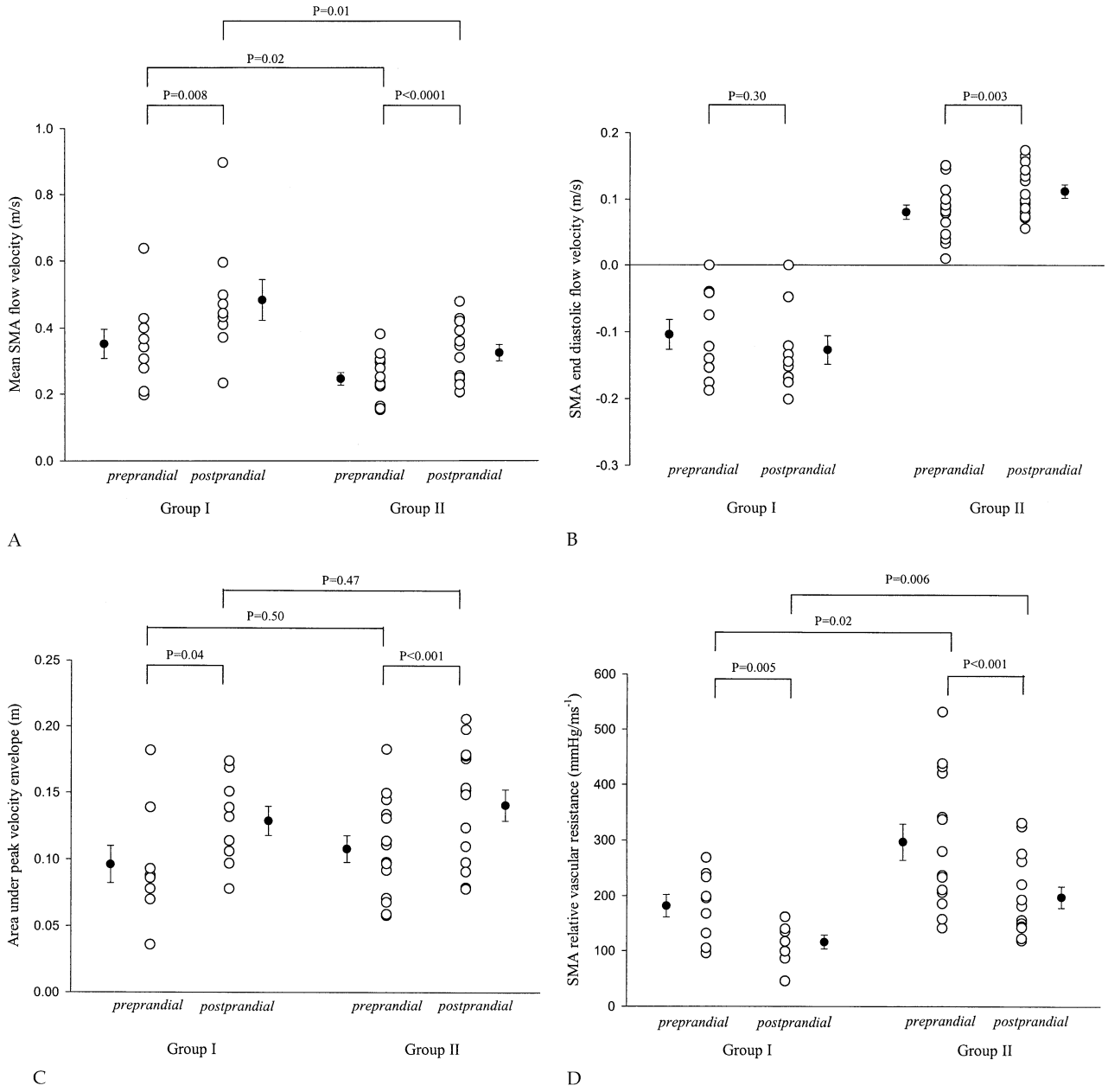

Fig 1. Vertical scatter plots of the superior mesenteric arterial (SMA)*: (A) time-averaged mean velocity, (B) end diastolic flow velocity, (C) area under peak velocity envelope, and (D) relative mesenteric vascular resistance. Intragroup comparison of preprandial and postprandial hemodynamic variables was performed using paired* t *tests while intergroup comparison was performed using unpaired* t *tests.* Open circles *represent data of individual patients, while* solid circles *and* error bars *represent group means ± SEM.*

dependent cyanotic heart disease. Their demographic and clinical data are summarized in Table 1.

Effects of Enteral Feeding on Systemic and Splanchnic Hemodynamics

The postprandial changes in splanchnic hemodynamics are illustrated in Figure 1. In nonshunted group II patients the TAMV increased from 0.25 ± 0.07 to 0.33 ± 0.09 m/s ($p < 0.001$), EDFV from 0.08 ± 0.04 to 0.11 ± 0.04 m/s ($p = 0.003$), and AUPVE from 0.11 ± 0.04 to 0.14 ± 0.04 m ($p < 0.001$) postprandially, while the SMA relative vascular resistance decreased from 297 ± 121 to 198 ± 73 mm Hg/ms^{-1} ($p < 0.001$) postprandially. Likewise, in shunted group I patients the TAMV increased from 0.35 ± 0.13 to 0.48 ± 0.19 m/s ($p = 0.008$) and AUPVE from 0.10 ± 0.04 to 0.13 ± 0.03 m ($p = 0.049$) postprandially, while the SMA relative vascular resistance decreased from 182 ± 61 to 116 ± 38 mm Hg/ms^{-1} ($p = 0.005$) postprandially. In contrast the postprandial EDFV remained unchanged in the shunted patients ($p = 0.30$). In both groups no

Table 2. Postprandial Changes in Systemic Circulatory Hemodynamic Variables

Parameters	Group I			Group II		
	Preprandial	Postprandial	*p* Value	Preprandial	Postprandial	*p* Value
Cardiac output (ml/min/kg)	639 ± 176	711 ± 274	0.38	293 ± 88	311 ± 92	0.36
Systemic oxygen saturation (%)	87 ± 5	87 ± 5	0.71	92 ± 10	93 ± 9	0.09
Systolic blood pressure (mm Hg)	85.9 ± 8.0	76.2 ± 10.7	0.06	85.9 ± 10.7	86.6 ± 9.3	0.77
Diastolic blood Pressure (mm Hg)	48.1 ± 8.2	40 ± 9.1	0.03	53.6 ± 9.9	53.7 ± 10.1	0.98
Pulse pressure (mm Hg)	40.2 ± 12.4	36.3 ± 6.7	0.40	33.4 ± 6.3	34.9 ± 9.2	0.52

significant postprandial changes in systemic cardiac output, systemic oxygen saturation, systolic blood pressure, and pulse pressure were observed (Table 2). However, the diastolic blood pressure decreased significantly ($p = 0.03$) in group I patients after enteral feeding.

Group I Versus II Patients

Whereas basal and postprandial diastolic SMA blood flow was antegrade in group II patients, absent or retrograde diastolic flow (Fig 1B) was characteristic of the shunted group I patients both before (−0.10 ± 0.07 m/s) and after (−0.13 ± 0.06 m/s) feeding. Furthermore the relative SMA vascular resistance was significantly lower in group I as compared with group II patients both before (182 ± 61 versus 297 ± 121 mm Hg/ms^{-1}, $p = 0.02$) and after (116 ± 38 versus 198 ± 73 mm Hg/ms^{-1}, $p = 0.006$) feeding. On the other hand the TAMV was significantly higher in group I both before (0.35 ± 0.13 versus 0.25 ± 0.07 m/s, $p = 0.02$) and after (0.48 ± 0.19 versus 0.33 ± 0.09 m/s, $p = 0.01$) feeding. The AUPVE hence remained similar between the two groups ($p = 0.50$ preprandially, $p = 0.47$ postprandially; Fig 1C).

As for the systemic circulatory hemodynamic variables, group I patients had significantly higher basal cardiac output ($p < 0.001$). Their pulse pressure also tended to be larger (40.2 ± 12.4 versus 33.4 ± 6.3 mm Hg, $p = 0.09$), which was probably related to a lower diastolic blood pressure (Table 2).

Effect of Cyanosis

To assess whether differences observed between group I and II patients were related to hypoxemia, the SMA hemodynamic indicators of the 10 patients in group II who had acyanotic heart disease were compared with those of the remaining 4 who had cyanotic heart disease but not requiring shunt insertion (Table 3). Apart from having a significantly lower systemic oxygen saturation ($p < 0.001$), cyanotic patients did not differ from the acyanotic ones in terms of SMA flow hemodynamics both before and after enteral feeding.

Comment

This study provides evidence for the first time that the splanchnic circulation counteracts diastolic "steal" in infants after systemic-to-pulmonary arterial shunt insertion by lowering its vascular resistance. Whereas the absent or reversed diastolic superior mesenteric arterial blood flow observed in shunted infants is similar to that reported in symptomatic infants with patent ductus arteriosus, the significantly lower relative mesenteric vascular resistance in the former, both preprandially and postprandially probably represents an adaptive mechanism to protect the gut from ischemic insult.

In our group of nonshunted infants with either acyanotic or cyanotic congenital heart disease the values of

Table 3. Effect of Cyanosis on Superior Mesenteric Arterial Hemodynamic Variables

Variables	Acyanotic Patients (n = 10)	Nonshunted Cyanotic Patients (n = 4)	*p* Value
Systemic oxygen saturation (%)	98.2 ± 1.2	77.3 ± 5.6	<0.001
Time-averaged mean velocity (m/s)			
Preprandial	0.26 ± 0.08	0.22 ± 0.08	0.46
Postprandial	0.34 ± 0.10	0.30 ± 0.09	0.56
End-diastolic flow velocity (m/s)			
Preprandial	0.07 ± 0.04	0.11 ± 0.03	0.18
Postprandial	0.11 ± 0.04	0.13 ± 0.04	0.48
Area under peak velocity envelope (m)			
Preprandial	0.11 ± 0.04	0.10 ± 0.04	0.63
Postprandial	0.15 ± 0.05	0.13 ± 0.04	0.57
Relative vascular resistance (mmHg/ms^{-1})			
Preprandial	289 ± 113	317 ± 158	0.72
Postprandial	194 ± 82	208 ± 56	0.75

their various SMA blood flow indices, namely TAMV, EDFV, relative vascular resistance, and AUPVE, were similar to previous reported values in healthy term infants [4, 5, 7]. Furthermore, the postprandial increase in flow velocities and area under peak velocity envelope and reduction in mesenteric vascular resistance parallel that of normal term infants [4, 5, 7]. Such increase in velocities is believed to reflect a genuine increase in flow volume as the SMA diameter increases rather than decreases after a feed [5]. Furthermore the observed postprandial increase in splanchnic blood flow velocity in healthy infants and our group of patients is probably accomplished by intestinal vasodilation as indicated by the decrease in mesenteric vascular resistance [7]. However, the physiologic control mechanism or mediator of changes of the splanchnic circulation in response to feeding remains to be clarified although both central and local control mechanisms seem to be operating to effect such changes [5].

In shunted patients the absence or reversal of diastolic flow parallels that of infants with symptomatic patent ductus arteriosus [1]. However, in none of the clinical studies have the impact of a patent ductus arteriosus on relative mesenteric vascular resistance been assessed. In an animal study using near-term fetal lambs [8] the terminal ileum blood flow was significantly lower and the vascular resistance significantly higher in the presence of a patent ductus as compared with that after ductal ligation despite an unchanged ileum perfusion pressure. In contrast in our shunted patients, both the basal and postprandial relative mesenteric vascular resistance is significantly lower than those of nonshunted ones. This suggests that the splanchnic circulation behaves differently between shunted patients and those with a patent ductus arteriosus.

The lowering of basal and postprandial relative mesenteric vascular resistance in the presence of a systemic-pulmonary arterial shunt may represent an adaptive mechanism to counteract the potential diastolic steal through the shunt. This has important implications as previous studies in animals with surgically created aortopulmonary shunts showed that surface cooling, an adjunct to cardiopulmonary bypass, causes maldistribution of cardiac output with reduced blood flow to the viscera and kidneys [9]. That a lowering of SMA relative resistance might confer protection to the gut is perhaps reflected by the absence of data in the literature to support an association between intestinal ischemia or enterocolitis and shunting. The underlying mechanism remains unclear however. Nonetheless, it is unlikely to be related to chronic hypoxaemia as no differences could be discerned between nonshunted cyanotic and acyanotic patients (Table 3). It is possible, however, that the larger pulse pressure in the shunted infants might have led to greater stretching of the smooth muscles, and hence greater increase in cross-sectional area of the blood vessels [10]. Increased flow through the mesenteric arterioles may then lead to vasodilation and hence a reduction in vascular resistance, possibly through augmentation of nitric oxide release by the endothelium [11, 12]. Although such an argument might also apply to preterm or term infants with a large patent ductus arteriosus the phenomenon of myogenic vasoconstriction in response to an elevation in intravascular pressure, shown to occur predominantly in young animals [12], might have led to an increase in mesenteric vascular resistance instead [8].

While gut perfusion may be relatively preserved in shunted infants in light of the observed reduction in basal and postprandial mesenteric vascular resistance, this protective mechanism is operating at the expense of a reduction in splanchnic flow reserve. It is possible therefore that tolerance of the gut in shunted infants to systemic hypoperfusion may still be compromised.

References

1. Coombs RC, Morgan MEI, Durbin GM, et al. Gut blood flow velocities in the newborn: effects of patent ductus arteriosus and parenteral indomethacin. Arch Dis Child 1990;65:1067–71.
2. Cooke RWI, Meradji M, Villeneuve YVD. Necrotizing enterocolitis after cardiac catheterization in infants. Arch Dis Child 1980;55:66–8.
3. Leung MP, Chau KT, Hui PW, et al. Necrotizing enterocolitis in neonates with symptomatic congenital heart disease. J Pediatr 1988;113:1044–6.
4. Leidig E. Pulsed Doppler ultrasound blood flow measurements in the superior mesenteric artery of the newborn. Pediatr Radiol 1989;19:169–72.
5. Coombs RC, Morgan MEI, Durbin GM, et al. Doppler assessment of human neonatal gut blood flow velocities: postnatal adaptation and response to feeds. J Pediatr Gastroenterol Nutr 1992;15:6–12.
6. Pezzati M, Biagiotti R, Vangi V, et al. Changes in mesenteric blood flow in response to feeding: conventional versus fiber-optic phototherapy. Pediatrics 2000;105:350–3.
7. Martinussen M, Brubakk A, Linker DT, et al. Mesenteric blood flow velocity and its relation to circulatory adaptation during the first week of life in healthy term infants. Pediatr Res 1994;36:334–9.
8. Meyers RL, Alpan G, Lin E, et al. Patent ductus arteriosus, indomethacin, and intestinal distension: effects on intestinal blood flow and oxygen consumption. Pediatr Res 1991;29:569–74.
9. Mavroudis C, Gott JP, Katzmark S. The effect of suface cooling on blood flwo distribution in infant pig with mature left to right shunts. Cryobiology 1985;22:243–50.
10. Jacobson ED, Eldon C, Fondacaro JD. Hemodynamic effects of rapid injection into the canine superior mesenteric artery. Digest Dis Sci 1981;26:905–10.
11. Smiesko V, Lang DJ, Johnson PC. Dilator response of rat mesenteric arcading arterioles to increased blood flow velocity. Am J Physiol 1989;257:H1958–65.
12. Reber KM, Nowicki PT. Pressure and flow characteristics of terminal mesenteric arteries in postnatal intestine. Am J Physiol 1998;274:290–8.