Pediatr. Res. *14:* 1324–1327 (1980)

blood volume plasma volumes
hematocrit red cell mass
organs

Blood Volume and Hematocrit in Various Organs in Newborn Piglets

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Summary

Plasma volume and red cell mass of various organs in piglets aged 24 hr (n = 7) and 7 (n = 6), and 14 (n = 6) days were measured using ^{99m}Tc-labeled albumin and ^{51}Cr-labeled red blood cells. Organ activities were counted in a whole-body counter. Blood volume and hematocrit were calculated. The blood volumes in μl/g varied markedly between various organs. The lowest blood volumes at 24 hr of age were found in skin (21.9 ± 5.0 μl/g), brain (33.3 ± 8.4), and skeletal muscle (35.5 ± 7.4). The highest values at this age were noted in liver (670.0 ± 89.1), lung (533.8 ± 80.7), spleen (332.0 ± 82.8), and kidney (300.6 ± 55.5). Blood volumes of about 150 μl/g were observed in heart muscle and thyroid gland and those of about 100 μl/g in thymus and gastrointestinal tract. The total blood volume was 100.2 ± 3.9 μl/g at 24 hr and remained unchanged during the first 2 wk of life. A significant decrease in relative blood volume with growth was noted in liver and lung (P < 0.01), and in skeleton (P < 0.05). The blood volume, contained in the great vessels outside the organs, increased from 29.5 ± 5.5% of total blood volume at 24 hr to 31.2 ± 5.7% at 7 days and to 38.2 ± 7.5% at 14 days of life. The total body/venous hematocrit ratio was about 0.84. Accordingly, tissue hematocrits of most organs were below the venous hematocrit. Only in spleen was the tissue/venous hematocrit ratio (TH/VH) higher than 1.0. TH/VH of brain, gastrointestinal tract, thyroid gland, and thymus approached unity. The lowest TH/VH was found in kidney (0.54 ± 0.08 at day 1). In skin, the TH/VH decreased from 0.98 ± 0.10 to 0.82 ± 0.07 during the first 2 wk of life.

Speculation

Marked decrease of blood volume per g of tissue in liver, skeleton, and gastrointestinal tract with growth indicate high metabolic activity shortly after birth, which diminishes later on. Low blood content of the great vessels at day 1 should mean diminished tolerance to acute blood loss. Low organ hematocrits may be due to a more rapid flow of red blood cells than of plasma and to plasma skimming.

Regional distribution of blood volume has been extensively studied in adult animals (1, 2, 5, 8, 9, 12, 23, 30, 33, 40). Little is known about blood volume in organs of newborn animals. Smith *et al.* (35) measured the residual blood volume of several organs in newborn puppies that were killed by bleeding. Others have determined the pulmonary blood volume in newborn animals (3, 24, 41). The distribution of total blood volume upon various organs of newborn animals has not been investigated. In the present paper, results are presented on the red cell mass, plasma volume, blood volume, and hematocrit of several organs of developing piglets.

ANIMALS AND METHODS

Piglets out of 4 litters (German Landrace) were studied at 24 hr (n = 7) and 7 (n = 6) and 14 days (n = 6), respectively. They were born to healthy sows at known full term. All piglets were suckled by their mothers. They were not treated with iron. The right atrium was cannulated with polyethylen catheters via the right external jugular vein for injection and withdrawal of blood. Each piglet received local analgesia with procaine at the site of catheterization, but no systemic drugs. Two ml of blood were withdrawn from the catheter and centrifuged for 5 min at 1000 × g. The red blood cells were labeled with ^{51}chromium (17). Salt-poor human serum albumin (25%) was labeled by means of a commercial kit for electrolytic preparation of ^{99m}technetium (New England Nuclear Corp., North Billerica, MA). Each preparation of ^{99m}Tc-labeled albumin was carefully checked for particulate matter, turbidity, and pH (6). Labeling efficiency was determined with trichloracetic acid and membrane filtration (14). Batches containing more than 1% of unbound ^{99m}Tc were discarded. One postmix blood sample of 1 ml was taken 10 min after injection of labeled red blood cells and 5 min after injection of labeled albumin. Previous equilibration studies have shown that mixing of red blood cells and of albumin are complete within that period (16). Loss of albumin from the intravascular space has been found negligible in this short time. The piglets were killed immediately after the labeling and blood collecting procedure by injection of 2 mval KCl via the catheter.

At the immediately following autopsy, the large vessels were ligated close to their insertion at the organs and cut. All organs were removed using an electrocauteriser. Skin, muscles, and skeleton were separated. All organs were weighed, and the activities were counted immediately in a whole-body counter (4). *In vitro* studies showed a counting error of less than 2%. The radioactivity of the blood in the great vessels and of the small amount of blood lost from the organs ("residual blood") was also determined. Organ red cell mass and plasma volume were obtained by comparison of ^{51}Cr- and ^{99m}Tc-activities of the tested organ and the relevant standard. The ^{99m}Tc-counts were corrected for the ^{51}Cr-counts appearing in the ^{99m}Tc window. The ^{51}Cr activity was measured again when no ^{99m}Tc activity was present anymore. For measurement of total red cell mass and plasma volume, activities of 0.5 ml of blood and of the standards were counted in a well-type scintillation counter. Total body and organ hematocrits were calculated from the ratio of the corresponding red cell mass and blood volume values. Venous hematocrit was determined by the microhematocrit method using a correction factor of 0.97 for trapped plasma (16).

RESULTS

The mean red cell mass, plasma volume, and blood volume values, together with the weights and the hematocrit data for the total body and for each of the different organs, are shown in Table 1. Venous hematocrit decreased from 0.356 ± 0.030 at 24 hr (group I) to 0.303 ± 0.049 at 7 days (group II), and to 0.233 ± 0.041 at 14 days of extrauterine life (group III). Inasmuch as total blood volume (TBV) related to body weight did not change during these 2 wk, total red cell mass decreased according to the venous hematocrit. The blood volumes varied considerably between dif-

Table 1. *Mean values of weight (in g), of red cell mass, plasma volume, and blood volume (in µl/g), and of tissue/venous hematocrit ratio (TH/VH) of various organs of piglets aging 24 hr (I), 7 (II) and 14 (III) days*

	Weight			Red cell mass			Plasma volume			Blood volume			TH/VH		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
Total body	1526	2031	4956	29.6	24.6	18.7	70.6	71.0	77.2	100.2	95.6	95.9	0.827	0.848	0.835
	±235	±259	±987	±3.9	±4.4	±3.7	±3.1	±4.2	±4.3	±3.9	±2.8	±4.0	±0.44	±0.047	±0.056
Brain	33.8	36.5	44.3	12.1	11.2	7.9	21.2	22.9	24.6	33.3	34.1	32.5	1.035	1.098	0.982
	±1.6	±1.6	±2.1	±3.3	±2.5	±3.8	±5.8	±5.4	±3.3	±8.4	±6.0	±6.5	±0.187	±0.147	±0.154
Lung	26.4	32.0	71.6	149.9	104.9	62.3	383.9	304.9	273.3	533.8	409.8	335.6	0.790	0.844	0.816
	±5.9	±6.7	±11.9	±38.2	±29.4	±5.3	±48.2	±57.0	±55.8	±80.7	±76.6	±54.4	±0.158	±0.075	±0.050
Heart	11.3	16.1	30.0	39.9	34.3	25.6	114.2	111.9	123.7	154.1	146.2	149.3	0.719	0.752	0.751
	±3.0	±5.1	±4.7	±13.5	±15.3	±4.7	±14.2	±26.8	±23.3	±23.6	±41.2	±23.3	±0.167	±0.081	±0.093
Kidney	13.1	15.6	30.6	57.5	41.9	23.8	243.1	248.1	248.3	300.6	290.0	272.1	0.544	0.475	0.370
	±2.7	±5.4	±6.6	±11.6	±13.7	±10.0	±44.6	±50.3	±17.3	±55.5	±58.7	±14.8	±0.079	±0.076	±0.098
Spleen	1.82	5.01	9.0	127.0	89.7	85.7	205.0	171.3	211.5	332.0	261.0	297.2	1.096	1.117	1.258
	±0.30	±0.57	±1.6	±25.2	±33.4	±16.5	±59.5	±32.6	±53.9	±82.8	±62.0	±51.8	±0.133	±0.089	±0.169
Liver	51.2	67.2	177.1	211.0	122.3	74.9	459.0	385.2	333.4	670.0	507.5	408.3	0.884	0.792	0.798
	±14.1	±21.8	±33.0	±47.8	±29.7	±22.8	±66.3	±59.7	±70.5	±89.1	±81.3	±93.0	±0.145	±0.078	±0.151
GI-tract	113.9	192.6	342.6	32.4	21.8	16.3	59.1	53.3	55.1	91.5	75.1	71.4	0.994	0.981	0.977
	±19.9	±10.0	±68.5	±12.1	±6.8	±4.6	±18.3	±19.2	±8.6	±27.2	±24.0	±12.2	±0.272	±0.149	±0.106
Muscle	346.1	564.3	1,543.1	10.6	9.7	7.4	24.9	28.2	28.5	35.5	37.9	35.9	0.843	0.825	0.847
	±94.4	±238.5	±389.5	±2.6	±3.8	±3.5	±5.7	±5.1	±7.2	±7.4	±8.4	±9.0	±0.147	±0.087	±0.148
Skeleton	435.6	491.1	990.3	15.0	13.7	9.9	46.1	41.2	38.8	61.1	54.9	48.7	0.699	0.829	0.860
	±71.0	±80.0	±178.2	±2.6	±3.3	±3.1	±8.7	±8.7	±3.9	±10.2	±10.9	±4.7	±0.116	±0.080	±0.091
Skin	239.9	372.8	1,025.7	7.6	7.4	4.5	14.3	22.4	18.2	21.9	29.8	22.8	0.977	0.822	0.808
	±41.0	±51.1	±166.7	±1.7	±1.7	±1.3	±3.8	±5.2	±3.7	±5.0	±6.1	±4.9	±0.098	±0.069	±0.064
Thyroid	0.37	0.57	1.33	53.1	42.8	36.3	102.0	100.2	105.7	155.1	143.0	142.0	0.970	0.985	1.096
	±0.16	±0.26	±0.68	±16.4	±10.2	±12.5	±32.5	±13.2	±16.3	±46.8	±16.5	±21.4	±0.095	±0.086	±0.209
Thymus[1]	1.85	2.29		50.0	14.9		61.5	34.8		111.5	49.7		1.167	0.937	
	3.73	0.85		18.5	14.2		34.7	54.6		53.2	68.8		1.051	0.983	
	2.04	1.20		21.4	14.3		43.0	33.8		64.4	48.1		0.999	1.025	

[1] Single values.

ferent organs. The liver contained the highest blood volume related to organ weight, and the brain contained the lowest. There was a tendency to reduction of blood volumes per g of tissue in most organs with age. A significant decrease was found in the skeleton from days 1 to 14 ($P < 0.05$), and in the lung and liver from days 1 to 7 ($P < 0.01$) with further reduction in the second wk of life. In the skin, however, blood volume increased during the first 7 days ($P < 0.05$) and decreased in the second wk to the values of day 1. Red cell mass decreased in all organs with age.

The organ blood volumes expressed as percentages of TBV are shown in Figure 1. The largest portion was found in the liver. The brain contained only 0.74% of TBV at 24 hr. These figures decreased markedly in most organs with age, resulting in reduction of the combined blood volumes in all organs. The residual blood volumes reflecting mainly large vessels outside of organs increased correspondingly from 29.5 ± 5.5% at 24 hr and 31.2 ± 5.7% at 7 days to 38.2 ± 7.5% of TBV at 14 days of life. The combined blood volumes detected in all organs including the residual blood volume was 103.4 ± 6.7% of TBV at 24 hr, 96.6 ± 8.9% at 7 days, and 94.4 ± 6.7% at 14 days of life. Thus, the sum of all single blood volume measurements exceeded the actual blood volume on average by 3% at 24 hr, whereas at 7 and 14 days 3.4 and 5.6%, respectively, were undetected.

The tissue hematocrits showed marked differences. In the spleen, the hematocrit was higher than the venous hematocrit. In the brain, the gastrointestinal tract, the thyroid gland, and the thymus, hematocrits were similar to the venous values. Hematocrits in the other organs as well as the total body hematocrit were lower than the venous hematocrit. The skin hematocrit approximated the venous hematocrit in the 24-hr-old piglets and the total body hematocrit in the 7- and 14-day-old piglets. The lowest hematocrits were found in the kidney. The differences between the tissue and venous hematocrits are best reflected by the tissue/venous hematocrit ratios. The ratios increased significantly ($P < 0.05$) in the skeleton during the first wk and in the spleen during the first 2 wk of life. The ratios were significantly decreased ($P < 0.01$) in the kidney at 2 wk and in the skin at 7 and 14 days of life compared to the values found shortly after birth.

DISCUSSION

The methods for estimation of organ red cell mass and plasma volume need some critical comment. The method of killing the animals and the manipulation during dissection probably caused some shift of blood. The rapid freezing technique of small animals in liquid nitrogen appears to be more convenient. However, the freezing time for the deepest part of the abdominal cavity of rats weighing 250 g is about 2.5 min (9). The freezing times in the 6- to 20-fold heavier piglets would be considerably longer. It seems likely, therefore, that in piglets the freezing technique causes greater shifts of blood than our technique. Some change of blood distribution at death cannot be avoided by any procedure. The recovery rates of the labeled compounds (103.0, 96.6, and 94.4% of total blood volume in the piglets studied at days 1, 7, and 14, respectively) indicate sufficient reliability of the counting and sampling technique.

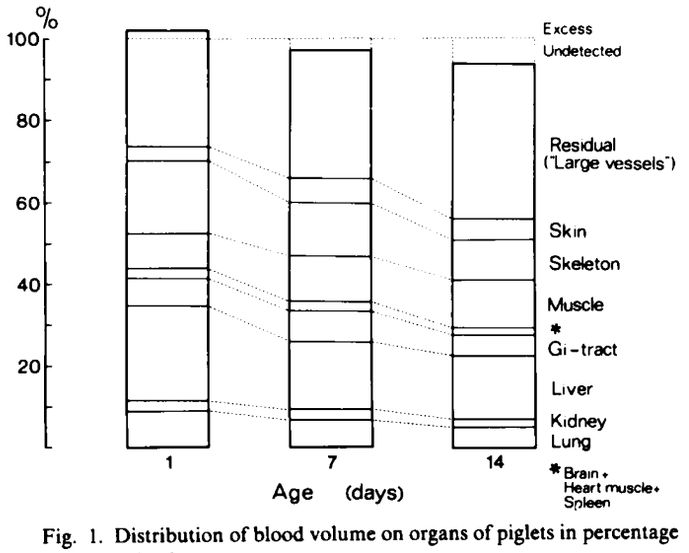

Fig. 1. Distribution of blood volume on organs of piglets in percentage of total blood volume.

The blood volume data in our study are difficult to compare to the results of other authors because the exact times of measurements during the first day are not given (7, 34, 37) or only plasma volume was determined (22, 26, 27). Plasma volume increases within hours after birth of the piglets as the result of absorption of intact proteins through the gut (22). Red cell mass also changes markedly during the first and second days of life (7, 34). Therefore, the reported hematocrits during the first day range from 0.27 to 0.35 liters/liter, and the red cell mass values vary between 20 and 32 ml/kg (7, 22, 26, 27, 34, 37). Red cell mass and hematocrit in piglets not treated with iron decreases markedly during the first 2 wk of life, whereas blood volume slightly decreases (37). The body/venous hematocrit ratio of about 0.84 measured in the piglets of all age groups agrees with the results of other studies (7, 16, 34). Our blood volume and hematocrit values are in the upper range of the data reported by other authors. Differences may be due to race peculiarities as different activity and proportion of fat in the body. Fat contains very little blood (21).

The striking differences in blood volumes per g of tissue between various organs of the piglets (Table 1) roughly agree with findings in adult rats (1, 5, 9, 23, 30, 33), dogs (8, 12), cats (40), and rabbits (2, 40). Regional distribution of blood volume in pigs has not been reported. There are some appreciable deviations of the piglets' organ blood volumes from those measured in adult animals. The blood volumes in the liver, skeleton, and gastrointestinal tract diminished markedly in the growing piglets, but the values of these organs measured in the 2-wk-old piglets were still above those noted in adult animals (2, 5, 9, 23, 30, 33). The decrease in blood volume of the liver and the skeleton coincides with reduction of erythropoiesis in these organs resulting from iron deficiency (11). The postnatal drop of blood volume in the gastrointestinal tract was not significant, but corresponds to decreasing blood flow to the gut of puppies (39).

The blood volume of the lung amounted to about one-half of the lung weight in the 24-hr-old piglets and decreased with age to values observed in adult rats (23, 33). Inasmuch as pulmonary blood volume and flow in air-ventilated lambs are closely correlated (41) and pulmonary blood flow increases with growth (13), we expected an increment rather than a downward trend in relative pulmonary blood volume of the piglets with age. It becomes obvious that mean transit time expressed as ratio of pulmonary blood volume and flow must decrease considerably during development of piglets. Low volume-to-flow ratios can also be judged for the brain, kidney, and heart muscle by comparison of our results with relevant blood flow data in piglets (13, 25, 29, 42).

The combined blood volumes of the 12 organs decreased progressively from 74 to 56% during the first 2 wk of life (Fig. 1). The organs of puppies killed by bleeding contain about one-half of the piglets' organ blood volumes at corresponding ages with a similar tendency to reduction with growth (35). Bleeding volumes of the puppies increased with age from 28% during the first day to 60% in puppies aged 41 to 56 days. This increase in bleeding volume corresponds to the increase in blood volume noted in the great vessels outside the organs of the piglets. This great vessels' blood volume does not represent the total large vessels' blood volume which amounts to about 80% of the total blood volume in adult dogs (12, 15). Nevertheless, it appears conceivable that our results together with the data on puppies indicate a smaller large vessels' blood volume in newborns than in adults. These differences could explain the diminished tolerance to acute blood loss of the newborn (31). Furthermore, increase in large vessels' blood volume with growth may increase venous return and thus contribute to rising cardiac output in piglets with age (13).

The hematocrit of the total blood in the body and of the blood

in most of the piglets' organs was lower than that of venous blood. The tissue/venous hematocrit ratios (TH/VH) determined by Smith *et al.* (35) in growing beagles killed by bleeding are in close agreement with our results. Only the TH/VH of the gastrointestinal tract was markedly lower than in the piglets. Inasmuch as Smith *et al.* (35) assumed that after bleeding blood was mainly contained in the small vessels, we expected higher TH/VH in the piglets than in the puppies. The corresponding results of the two different studies indicate that either the small vessels contribute considerably to the blood loss or the hematocrit is also decreased in the larger vessels inside the organs.

The skin hematocrit of the 24-hr-old piglets was similar to the venous hematocrit, but fell more than the venous hematocrit with growth. High skin hematocrit may likewise contribute to the tendency of the skin prick hematocrit to overestimate the venous hematocrit in newborn infants (20). The decreased hematocrits in most organs could not be outweighed by the high splenic hematocrit because the spleen of the piglets contained less than 1% of the total blood volume. However, when the spleen is considerably enlarged, the great amount of splenic blood may increase the total blood volume (18) and the body/venous hematocrit ratio (17).

The large differences in the TH/VH in various organs of the piglets are similar to those observed in adult rats (1, 9, 23, 30, 33), dogs (8, 12), cats (40), rabbits (2, 40), and hamsters (38). Special attention has been given to the renal hematocrit, which is about one-half that of the central circulation (8, 9, 12, 23, 28, 30, 33, 35, 38, 40). The origin of the "extra plasma" is obscure. Decreased organ hematocrits may be erroneously calculated if mixing of red cells is incomplete or labeled albumin has escaped to the extravascular space at the time of blood sampling. Indeed, the disappearance rate of labeled albumin in the newborn is markedly higher than in the adult (15, 17, 19) and is about 30%/hr in the newborn piglet (16). However, mean disappearance of albumin computed for the whole circulatory system is only about 2% within 5 min, and mixing of labeled red cells is complete within 10 min (16). Another explanation is based on the observation that the axial streaming red cells flow more rapidly through capillaries (32, 36) and tend to move into branches with fast flow resulting in plasma skimming in branches with slow flow (10). This implies that the hematocrit in organs with a large proportion of small vessels as the kidney, where about one-half of the blood volume is contained in capillaries, is low (38, 40).

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43. This work was presented in condensed form to the European Society for Pediatric Research, Venice, September 1977. Pediatr. Res. (Abstract), *11:* 1023 (1977).
44. The authors gratefully acknowledge the skillful technical assistance of M. Hoffmann and M. Güntner.

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46. This research was supported by Deutsche Forschungesgmeinschaft (SFB 147).
47. Received for publication October 15, 1979.
48. Accepted for publication March 3, 1980.

0031-3998/80/1412-1324$02.00/0

Printed in U.S.A.