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Original article

Whole blood and plasma amino acid transfers across the portal drained viscera and liver of the pig[1]

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Abstract — Whole blood (WB) and plasma (P) amino acid transfers across the portal drained viscera and the liver were determined during 6 h of a constant p-aminohippuric acid infusion in three hourly-fed Landrace × Large-White pigs (30.5 kg, mean live weight) surgically prepared with chronically inserted catheters in a mesenteric vein (MV), the portal vein (PV), an hepatic vein (HV) and the carotid artery (CA). Plasma and WB amino acid concentrations were determined in the CA, PV and HV. The plasma/WB ratios showed no significant differences for vessels except for lysine and glutamate for which this ratio is significantly higher in the HV and in the PV for lysine. This suggests that the PV lysine and HV glutamate were preferentially transported in the plasma. In the PV, threonine, valine and alanine are transported by both plasma and red blood cells. These data show that the contribution of plasma and whole blood to amino acid transport can be different between amino acids and between individual tissues. © Inra/Elsevier, Paris.

pig / amino acid / blood / plasma / liver / digestive tract

Résumé — Transport des acides aminés à travers les tissus drainés par la veine porte et le foie par le plasma et le sang chez le porc. Le transport des acides aminés à travers les tissus drainés par la veine porte et le foie par le plasma (P) et le sang (S) a été déterminé chez trois porcs d'une trentaine de kg, nourris en continu, durant 6 h d'une perfusion d'acide para-aminohippurique. Ces animaux étaient munis de quatre cathéters permanents dans une veine mésentérique, la veine porte, une veine hépatique et l'artère carotide. Les concentrations sanguines et plasmatiques des différents acides aminés et le débit sanguin ont été mesurées dans les différents vaisseaux. Les rapports P/S des concentrations ne sont pas significativement différents d'un vaisseau à l'autre à l'exception de ceux de l'acide glutamique et de la lysine qui sont plus élevés dans la veine sus-hépatique et dans la veine porte dans le cas de la lysine. Ceci suggère que la lysine absorbée et l'acide glutamique libéré par le foie seraient préférentiellement transportés par le plasma. Dans la veine porte, le transport de la

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thréonine, la valine et l'alanine serait assuré à la fois par le plasma et les érythrocytes. Les résultats de cette étude préliminaire tendent à montrer que les contributions du sang et du plasma au transport des acides aminés peuvent être différentes selon l'acide aminé et le vaisseau considérés. © Inra/Elsevier, Paris.

porc / acides aminés / sang / plasma / foie / tractus digestif

1. INTRODUCTION

Studies of amino acid (AA) metabolism often consider changes in concentrations or exchanges (appearance and disappearance) of AA between the blood plasma compartment and selected tissues. Many authors have demonstrated, however, a contribution of erythrocytes to inter-organ AA transport [6, 9, 10, 16]. Exchanges of AA between plasma and erythrocytes seem to be very slow which implies an independent contribution of these two compartments in the exchange of AA between whole blood and tissues [6]. Using multi-organ arterio-venous catheterization in dogs, Elwyn et al. [6] showed that AA are mainly transported in the plasma from the intestine to the liver, whereas transport from the liver to the other tissues occurs mainly in erythrocytes. Since erythocyte flow and balance are rather difficult to determine experimentally, erythrocyte contribution was commonly calculated from whole blood and plasma concentrations corrected by haematocrit. For this reason, whole blood concentrations are often considered rather than erythrocyte concentrations. Moreover, whole blood amino acid fluxes are more representative of total amino acid transfers across a tissue. In pigs, Rérat et al. [21] calculated amino acid balances across PDV tissues and the liver from whole blood and Keith et al. [12] reported an effect of diet on AA partitioning between plasma and whole blood sampled from the jugular vein. In this species, however, there are no data with which to compare the respective contribution of these two compartments to AA transport across a tissue. The aim of this preliminary study was to compare, in pigs fed a standard diet, AA transfers across the portal drained (PDV) area and the liver by plasma and whole blood in order to more accurately assess the inter-organ exchanges of AA in this species. In spite of the limited number of pigs, the results of this experiment provided interesting data on the contribution of blood and plasma to amino acid transport across the PDV and the liver. This model will be further used in studies comparing different nutritional statuses.

2. MATERIALS AND METHODS

2.1. Animals and infusion protocol

Three Large White × Landrace pigs (30.5 ± 2 kg live weight) from the Station de recherches porcines herd were surgically prepared under general anaesthesia with chronic insertion of catheters in a mesenteric (MV), the portal (PV) and an hepatic vein (HV) and in the carotid artery (CA). The hepatic catheter was introduced into the vessel directly through the liver tissue [17]. At least 10 days of post-surgery recovery were necessary before beginning the experiment.

In order to determine portal and liver blood flow, p-aminohippuric acid or PAH (Sigma France, Saint-Quentin Fallavier) was infused (0.2 $mg \cdot kg^{-1}$ BW/min) through the MV at a rate of 1 $mL \cdot min^{-1}$ for 6 h. The PAH solution was prepared with sterile physiological saline solution (9 g of $NaC \cdot L^{-1}$) and the pH was adjusted to 7.4 with NaOH before filtration through a 0.2 µm filter. Five millilitres of the same solution were used as a priming injection. Pigs were fed hourly with an automatic feeder in order to ensure a constant delivery of AA into the blood. The amount of the diet (1 200 ± 200 $g \cdot d^{-1}$) offered to the pigs was adjusted to the metabolic weight. The composition of the diet is described in *table I*. Blood (6 mL) was sampled in heparinized tubes from the PV, the HV and the CA every 30 min

Table I. Composition of the diets ($g \cdot kg^{-1}$).

Ingredients	
Barley	240
Wheat	243.85
Maize	150
Wheat bran	50
Soybean meal	230
Tallow	20
Molasses	30
Dicalcium phosphate	12
Limestone	14
Iodized salt	4.5
L-lysine HCl	0.65
Trace mineral and vitamin premix*	5

* For details of premix composition, see [14].

for PAH and AA concentration measurements. At the end of the experiment, pigs were killed with a lethal injection of pentobarbital into the carotid catheter and the positions of the catheters were verified in order to validate the accuracy of the surgical procedure.

Animal care and surgical procedures were performed according to the guidelines of the French Ministry of Agriculture and Fisheries.

2.2. Chemical analysis and calculations

The PAH concentration in whole blood was determined as described by Ortigues et al. [17] after a deacetylation step by acid hydrolysis. The blood flow rate was calculated according to the indicator-dilution technique [11]. Portal (PF) and hepatic (HVF) blood flow rates were calculated as $i_{PAH}/([PAH]_{PV} - [PAH]_A)$ and as $i_{PAH}/([PAH]_{HV} - [PAH]_A)$, respectively, where i_{PAH} is the rate of PAH infusion and $[PAH]_{PV}$, $[PAH]_A$ and $[PAH]_{HV}$ correspond to PAH blood concentration in the portal vein, the artery and the hepatic vein, respectively. Plasma PAH concentrations were then derived from blood PAH concentrations, corrected for haematocrit, in order to calculate plasma flow in the same way.

AA concentrations were measured in the plasma and whole blood after deproteinization with an equal volume of sulphosalicylic acid solution (60 and 120 $g \cdot L^{-1}$ for plasma and whole blood, respectively) by liquid chromatography and ninhydrin detection (Biotronik LC 5001, Biotronik, Pusheim Banhnof, Germany) using norvaline as an internal standard. In the current work, no sulphydryl protective reagent was included in the SSA solution. Even when P and WB samples were immediately deproteinized and frozen, we did not detect methionine in whole blood samples. As a consequence, we have chosen not to report sulphur AA data. In our experimental conditions, tryptophan concentration was not detected in a satisfactory manner (conservation and quantity of tryptophan, inadequate elution programme) and was not calculated. AA concentrations in erythrocytes were calculated with the following formula: $[AA]_{RBC} = ([AA]_{WB} - (1 - Ht).[AA]_P)/Ht$. Dietary amino acid contents were determined, after acid hydrolysis, by high pressure liquid chromatography (Alliance System, Waters France, Saint-Quentin-en-Yvelines) after precolumn derivatization with 6-aminoquinolyl-N-succinimidyl carbamate (AQC, AccQ.Fluor Reagent, Waters).

AA flux was calculated as the product of blood or plasma flow times the AA concentration. AA balance in the PV was calculated as follows: $([AA]_{PV} - [AA]_A) \times PF$, where PF is the portal blood or plasma flow. AA balance in the HV corresponded to the difference between the hepatic output ($[AA]_{HV} \times HVF$, where HVF is the hepatic vein blood or plasma flow) and the hepatic input through the portal vein ($[AA]_{PV} \times PF$) and the hepatic artery ($[AA]_A \times HAF$, where HAF is the hepatic artery plasma or blood flow calculated as the difference between HV flow and PV flow). Positive AA balance values reflect an appearance of AA in the portal vein or in the hepatic vein, whereas negative values reflect AA uptake by the PDV or by the liver.

2.3. Statistical analysis

All data were submitted to variance analyses according to the general linear model procedure (GLM) of SAS [22]. In order to control the steady state status of the animals, we first checked the non-significant effect of time on the different parameters. PAH infusion did not allow for a continuous determination of blood flow but gave an average value for blood flow. For these reasons, we chose to carry out the statistical analysis using average values for each animal. Because of the variance heterogeneity between vessels, amino acid fluxes were analysed separately. Dif-

ferences between WB and P for amino acid fluxes and balance and between vessels for P/WB were tested by the Fisher-Snedecor method and adjusted means were compared by the Student's *t*-test and declared significant at $P < 0.05$. Due to the high variability of our balance data, we have chosen a level of probability of $P < 0.1$.

3. RESULTS

During the 6 h of PAH infusion, there was no significant variation of the haematocrit. The steady states for amino acid concentrations and for P/WB were verified and are illustrated in *figure 1* for an essential, lysine, and a non-essential, alanine, amino acid. Plasma, whole blood and calculated erythrocyte AA concentrations in the carotid artery are presented in *table II*. Lysine, threonine, histidine, glycine, glutamate and aspartate were relatively more abundant in WB and erythrocytes than in P, whereas arginine, glutamine and asparagine were present in higher concentrations in P than in WB. Plasma to whole blood ratios of AA concentrations were calculated for different sampling points (*table III*). Except for lysine and glutamate, P/WB ratios showed no significant differences between blood vessels. The lysine P/WB ratio was significantly higher in the PV and the HV than in the CA, whereas the glutamic acid P/WB ratio was higher in the HV than in the other two vessels.

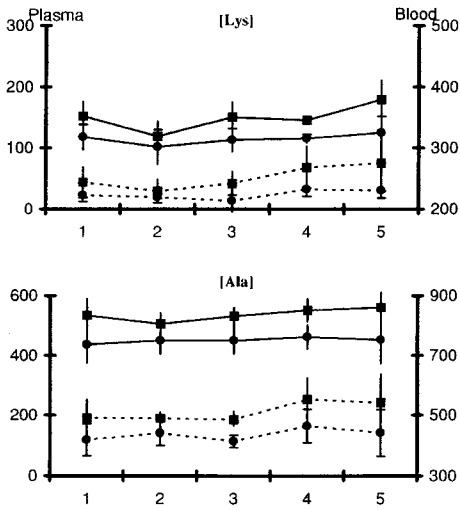

Figure 1. Carotid artery (●), portal vein (■) plasma and whole blood lysine and alanine concentrations ($\mu mol \cdot mL^{-1}$) during PAH infusion. Values are means ($n = 3$) with their standard errors represented by vertical bars. Unbroken lines correspond to P data and dashed lines correspond to WB data.

The portal vein amino acid balance was positive for all AA. Except for glutamic acid and glutamine, all PV balance values were significantly different from zero indicating a significant appearance of AA in the PV. The HV balance (*table IV*) showed negative values (AA removal from plasma or blood) but these values were not significantly different from zero for all AA except serine and alanine. Glutamic acid exhibited a positive balance significantly different from zero indicating a significant release of glutamic acid by the liver. For most AA, the PV balance was not different between WB and P. For threonine, valine and alanine, however, the blood balance was significantly higher than the plasma balance. There was no significant difference between the blood and plasma AA balance across the liver. In *figure 2*, we have expressed the portal AA balance as a percentage of digestible AA intake. Alanine appeared in the portal vein in large excess of the intake, whereas a low proportion of digested glutamic and aspartic acid appeared in the portal vein. The AA balance difference between P and WB was only significant for threonine, valine and alanine.

4. DISUSSION

We have chosen to restrict our discussion to the AA balance of plasma and whole blood data. Whole blood reflects the contribution of both plasma and erythrocytes and small differences between plasma and erythrocytes probably result in non-signifi-

Table II. Plasma, whole blood and calculated erythrocyte AA concentrations in the carotid artery (CA), portal vein (PV) and hepatic vein of pigs.[1]

	CA				PV				HV				P[3]
AA	P	WB	E[2]	SEM	P	WB	E[2]	SEM	P	WB	E[2]	SEM	
Lys	115	224	508	60	149	255	528	57	135	240	507	59	P^a WB^b E^c
Thr	192	210	259	12	207	232	275	14	199	216	260	13	P^a WB^b E^c
Val	355	354	349	8	373	378	370	7	362	364	367	11	NS
Leu	275	266	241	10	309	296	265	13	294	284	259	12	P^a WB^a E^b
Ile	189	173	132	10	209	191	145	13	201	180	166	13	P^a WB^a E^b
Phe	103	97	82	4	125	116	94	6	103	97	83	4	P^a WB^a E^b
His	86	95	119	6	91	95	136	7	107	102	129	7	P^a WB^b E^c
Arg	188	144	–	16	224	172	–	20	199	151	–	22	P^a WB^b
Gly	603	874	1 573	147	636	912	1 627	149	598	884	1 603	151	P^a WB^b E^c
Ala	450	436	399	22	536	517	468	21	430	430	428	31	NS
Ser	167	163	152	3	196	193	187	5	165	163	158	4	NS
Glu	289	438	826	86	291	453	877	95	494	564	746	46	P^a WB^b E^c
Gln	637	371	–	60	605	367	NE	54	583	349	–	50	P^a WB^b
Tyr	105	109	118	6	118	122	143	6	97	111	146	8	P^a WB^a E^b
Asp	17	47	127	17	23	54	134	17	20	53	137	18	P^a WB^b E^c
Asn	155	96	–	19	207	119	–	24	151	90	–	17	P^a WB^b

[1] Values are means (SE) for three pigs expressed in $\mu mol \cdot mL^{-1}$.
[2] Erythrocyte concentrations are calculated as described in text.
[3] Different letters indicate a significant difference ($P < 0.05$) between means of plasma (P), whole blood (WB) and erythrocyte (E) concentrations.
–: Non-estimated.

Table III. Plasma to whole blood (P/WB) ratios of AA concentrations in the carotid artery (CA), portal vein (PV) and hepatic vein (HV).

	CA	PV	HV
Lys	$0.51^{a} \pm 0.02$	$0.58^{b} \pm 0.02$	$0.56^{b} \pm 0.02$
Thr	0.91 ± 0.02	0.90 ± 0.04	0.92 ± 0.01
Val	1.003 ± 0.02	0.98 ± 0.02	0.99 ± 0.02
Leu	1.03 ± 0.03	1.04 ± 0.04	1.03 ± 0.006
Ile	1.09 ± 0.02	1.09 ± 0.05	1.11 ± 0.02
Phe	1.06 ± 0.02	1.08 ± 0.03	1.06 ± 0.02
His	0.91 ± 0.03	0.91 ± 0.02	0.88 ± 0.01
Arg	1.31 ± 0.03	1.31 ± 0.05	1.32 ± 0.03
Gly	0.69 ± 0.005	0.69 ± 0.01	0.68 ± 0.01
Ala	1.03 ± 0.005	1.03 ± 0.02	0.99 ± 0.02
Ser	1.02 ± 0.02	1.01 ± 0.02	1.01 ± 0.01
Glu	$0.66^{a} \pm 0.08$	$0.64^{a} \pm 0.09$	$0.87^{b} \pm 0.06$
Gln	1.72 ± 0.09	1.66 ± 0.1	1.68 ± 0.1
Tyr	0.97 ± 0.08	0.95 ± 0.08	0.87 ± 0.02
Asp	0.36 ± 0.05	0.42 ± 0.05	0.38 ± 0.04
Asn	1.8 ± 0.11	1.76 ± 0.17	1.54 ± 0.25
Orn	0.71 ± 0.02	0.69 ± 0.03	0.68 ± 0.01
Pro	0.97 ± 0.03	0.98 ± 0.02	0.93 ± 0.01

Values are means ± SE for three pigs. On the same line, means with different superscripts are significantly different from each other ($P < 0.05$).

cant differences between plasma and whole blood. Because erythrocyte data were obtained by calculation, erythrocyte balance data were too variable to be considered.

4.1. AA concentration gradients between plasma and erythrocytes

It is now accepted that both plasma and erythrocytes may contribute to amino acid transport between tissues. Our data implied some differences in the partitioning of AA between plasma and erythrocytes (*table I*). Lysine, threonine, histidine, glycine, glutamic acid and aspartic acid were relatively more abundant in erythrocytes than in plasma, whereas arginine, glutamine and asparagine were less concentrated in erythrocytes. These results are consistent with data presented by Keith et al. [12] for pigs and sheep [16] but not for dogs (for glutamic acid and glycine) [5], and calves (for lysine and threonine) [10]. The existence of an AA concentration gradient across the erythrocyte membrane may have different origins. 1) The presence of a transport system in the erythrocyte membrane controlling the rate of exchange of intracellular AA with plasma. 2) Intracellular AA may be provided by proteins or peptide proteolysis or by de novo synthesis for non-essential AA. 3) The utilization of AA for erythrocyte metabolism could reduce the intracellular AA concentration. For example, the absence (calculated) of arginine in erythrocytes is probably the consequence of the presence of intracellular arginase activity [26]. 4). The nutritional status of the animals, which affects the respective size of the two erythrocyte pools. Proenza et al. [19] identified two erythrocyte pools: an intracellular pool and a rapid turnover pool of adsorbed amino acids which probably

Table IV. Portal vein (PV) and hepatic vein (HV) plasma and whole blood (WB) AA balance ($\mu mol \cdot kg^{-1} \cdot h^{-1}$).

	PV				HV			
	Plasma	WB	SEM	p	Plasma	WB	SEM	p
Lys	87	88	8.6	NS	–30	–44	28	NS
Thr	41	61	1.3	0.008	–18	–50	22	NS
Val	41	73	1.2	0.003	–24	–45	35	NS
Leu	85	83	8.6	NS	–31	–33	24	NS
Ile	52	48	2.6	NS	–15	–32	14	NS
Phe	53	53	4.4	NS	–53	–52	6	NS
Arg	86	78	11.8	NS	–59	–65	24	NS
His	34	44	7.1	NS	–23	–26	6	NS
Gly	86	82	7.7	NS	–92	–90	69	NS
Ala	213	232	3.7	0.068	–266	–293	39	NS
Ser	77	65	15.6	NS	–75	–100	12	NS
Glu	4	18	21.5	NS	551	416	64	NS
Gln	–66	–55	18.7	NS	–67	–65	44	NS
Tyr	31	46	6.3	NS	–57	–36	9	NS
Asp	15	19	1.3	NS	–4	0	56	NS
Pro	127	139	13.4	NS	–101	–52	31	NS

Values are means ($n = 3$). NS: Non-significant.
Glu and Gln PV balances are not significantly different from zero. All values for HV balance are not different from zero except Ala, Ser and Glu.

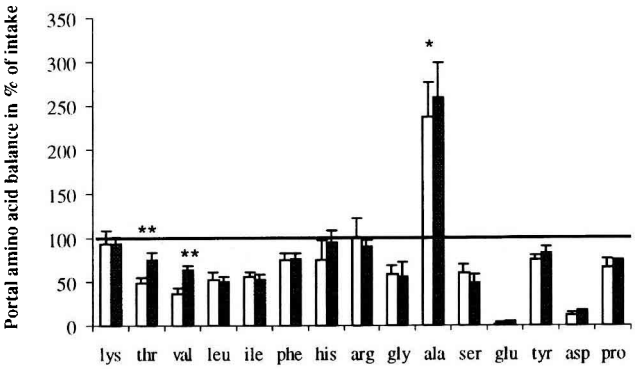

Figure 2. Portal plasma (□) and whole blood (■) AA balance expressed as a percentage of dietary AA intake. Values are means ($n = 3$) with their standard errors represented by vertical bars. * The difference between blood and plasma is significant at $P < 0.1$; ** the difference between blood and plasma is significant at $P < 0.05$.

plays a role during starvation [18]. In the present study, we could not distinguish between these two compartments in blood cell amino acids.

Glutamate is one of the most abundant AA in the intracellular fluid and one of the least concentrated in the plasma. This could explain why we were unable to show any increase in plasma glutamate concentration in pigs fed a glutamate supplemented diet

[14]. Another and more likely explanation is, however, that glutamate given orally is taken up and metabolized by the intestinal tissues [1, 20, 24]. When comparing plasma and whole blood AA concentrations, Hagenfeldt and Arvidsson [8] assumed that glutamate and aspartate are transported in erythrocytes through a highly concentrative transport system. Erythrocytes were found, however, to be impermeable to L-aspartate and L-glutamate in vitro [26] and in vivo [9]. In humans, using ^{15}N labelled glutamate, Darmaun et al. [2] reported a strong compartmentalization of glutamate between plasma and erythrocytes since only 4 % of erythrocyte glutamate exchanged with plasma glutamate. As a consequence, intracellular glutamate could come from the transamination of 2-oxoglutarate and/or the hydrolysis of a glutamate-rich protein or peptide. Darmaun et al. [3] proposed that high glycine intracellular concentrations could be maintained by glutathione hydrolysis. The same explanation could apply to the erythrocyte intracellular glutamate concentration.

The presence of a high lysine concentration in erythrocytes is a common observation in many species although the origin of red cell lysine is difficult to explain. The existence of a highly concentrative transport system for this AA seems, however, to be unlikely since the initial rate of lysine uptake is low compared to those observed for other AA [26]. Moreover, in rats, Felipe et al. [7] described a transport system which is close to the diffusion process and consequently plasma lysine concentration dependent.

4.2. AA transfers across the liver and the PDV

In order to explain the concentration gradient of AA between erythrocytes and plasma, we have to consider the exchanges of AA between blood and tissues. Elwyn et al. [6] suggested a different contribution of plasma and erythrocytes to AA transport to and from the liver of dogs. In their scenario, AA would be transported from the intestine to the liver and from peripheral tissues to the intestine through the plasma, whereas AA would be transported from the liver to peripheral tissues in the erythrocytes. Similar results were reported in calves [10].

The sampling site did not affect P/WB ratios except for glutamate and lysine. For lysine, our data showed that this ratio is significantly higher in the PV and the HV than in the CA. This result implies an independent contribution of plasma and erythrocytes in lysine exchange between the blood and the PDV. The most likely hypothesis is that dietary lysine appearing in the portal blood is mainly transported in the plasma. Indeed, Lobley et al. [16] infused U-^{13}C AA into sheep and showed that plasma AA are always less enriched in the portal vein than in the artery, whereas in the erythrocytes the enrichment was not diluted by unlabelled dietary AA. Similarly, in calves, it was suggested that absorbed AA are mainly transported to the liver through the plasma [10]. In spite of the difference in lysine concentration between plasma and erythrocytes, there was no difference between the hepatic lysine balance calculated from plasma and that calculated from whole blood data (*table IV* and *figure 2*). This finding implies that erythrocyte lysine is less exchangeable than plasma lysine. Consequently, we suggest that the compartmentalization of lysine into the erythrocytes may contribute to spare this AA for utilization in peripheral tissues. In order to test this hypothesis, it would be interesting to compare the P and WB lysine balance across the PDV, liver and peripheral tissue balances with different suboptimal and optimal dietary lysine supplies. Comparison of plasma and blood AA balance (*table IV*) showed that, in contrast to lysine, threonine, valine and alanine portal vein balances were higher when calculated with blood than with plasma data. This suggests that dietary AA appeared in the PV in both plasma and blood (erythrocytes). The same hypothesis has been suggested for threonine and glycine in sheep [16]. The other AA would be transported mainly in the PV by

plasma. The amounts of threonine and branched chained amino acids appearing in the portal according to the intake are low (*figure 2*). This is probably the consequence of an intensive utilization of these amino acids by the digestive tract [21, 23], notably, in the case of threonine, for digestive endogenous protein synthesis [4].

Except for glutamic acid, all AA exhibit a negative HV balance. The high positive value of the HV glutamate balance (glutamate is released by the liver) compared to the low value of glutamate PV balance suggests an important glutamate synthesis in the liver. Considering the variation of the glutamate P/WB ratio, we have concluded that glutamate, released from the liver, is mainly transported by plasma. This observation seems to be confirmed by the trend towards a higher HV balance for glutamate calculated from plasma data than from whole blood data. Compared to the essential AA, the liver removes a great part of the glycine, alanine, serine and glutamine released by PDV. The large influx of these AA into the liver is probably used for gluconeogenesis and urea synthesis. The low ratio of essential to non-essential AA concentrations in the blood and plasma arriving at the liver supports the hypothesis of competition between essential and non-essential AA for transport into the liver. In particular, competition would be likely to occur between threonine and an intestinal metabolite of glutamic acid for threonine transport into the liver especially under conditions of low dietary threonine supply [13]. The large portal flux of alanine (a product of intestinal glutamic acid metabolism [25]) suggests that alanine may compete with threonine for entry into the liver [15].

The results reported in this preliminary study have shown that in pigs, erythrocytes take part in AA exchanges across the liver and the PDV. In the PV, threonine, valine and alanine seem to be transported both in the erythrocytes and in the plasma, whereas the other AA may be transported mainly in the plasma. The existence of an important concentration gradient across the red blood cell membrane for lysine and glutamate implies a compartmentalization of their metabolism. For these two AA, however, it seems that the plasma is the most readily exchangeable pool. This study has examined AA fluxes and balance across the PDV and the liver in pigs fed a standard well-balanced diet. It would be interesting, however, to compare different nutritional states and different AA dietary balances in order to better understand the respective role of the blood and the plasma in the wider control of liver metabolism of AA in the pig. Considering the difference between blood and plasma for some amino acid concentrations and fluxes, whole blood data should be considered as the most reliable. Moreover, balances calculated from whole blood reflect more accurately the total transfer of amino acids across a tissue or an organ. However, in studies using tracer infusion, the choice of pool where isotope dilution should be measured needs to be carefully considered according to the partition of each amino acid between plasma and erythrocytes.

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REFERENCES

[1] Battezzati A., Brillon D.J., Matthews D.E., Oxidation of glutamic acid by the splanchnic bed in humans, Am. J. Physiol. 269 (1995) E269–276.

[2] Darmaun D., Matthews D.E., Bier D.M., Glutamine and glutamate kinetics in humans, Am. J. Physiol. 251 (1986) E117–126.

[3] Darmaun D., Froguel P., Rongier M., Robert J.J., Amino acid exchange between plasma and erythrocytes in vivo in humans, J. Appl. Physiol. 67 (1989) 2383–2388.

[4] De Lange C.F.M., Sauer W.C., Souffrant W., The effect of protein status of the pig on the recovery and amino acid composition of endogenous protein in digesta collected from the distal ileum, J. Anim. Sci. 67 (1989) 755–762.

[5] Drewes L.R., Conway W.P., Gilboe D.D., Net amino acid transport between plasma and erythrocytes and perfused dog brain, Am. J. Physiol. 233 (1977) E320–325.

[6] Elwyn D.H., Launder W.J., Parikh H.C., Wise E.M., Roles of plasma and erythrocytes in interorgan transport of amino acids in dogs, Am. J. Physiol. 222 (1972) 1333–1342.

[7] Felipe A., Vinas O., Remesar X., Cationic and anionic amino acid transport studies in rat red blood cells, Biosci. Rep. 10 (1990) 527–535.

[8] Hagenfeldt L., Arvidsson A., The distribution of amino acids between plasma and erythrocytes, Clinica Chimica Acta 100 (1980) 133–141.

[9] Heitmann R.N., Bergman E.N., Transport of amino acids in whole blood and plasma of sheep, Am. J. Physiol. 239 (1980) E242–E247.

[10] Houlier M.L., Patureau-Mirand P., Durand D., Bauchart D., Lefaivre J., Bayle G., Transport des acides aminés dans l'aire splanchnique par le plasma sanguin et le sang chez le veau preruminant, Reprod. Nutr. Dev. 31, (1991) 399–410.

[11] Katz M.L., Bergman E.N., Simultaneous measurements of hepatic and portal venous blood flow in the sheep and dog, Am. J. Physiol. 216 (1969) 946–952.

[12] Keith M.O., Botting H.G., Peace R.W., Dietary effects on the concentration of free amino acids in plasma and whole blood of pigs, Can. J. Anim. Sci. 57 (1977) 295–303.

[13] Le Floc'h N., Régulation nutritionnelle de l'oxydation de la thréonine chez le porc, Ph. D. thesis, Université d'Aix-Marseille-II, 1995.

[14] Le Floc'h N., Seve B., Henry Y., The addition of glutamic acid or protein to a threonine-deficient diet differentially affects growth performance and threonine dehydrogenase activity in fattening pigs, J. Nutr. 124 (1994) 1987–1995.

[15] Le Floc'h N., Obled C., Seve B., In vivo threonine oxidation rate is dependent on threonine dietary supply in growing pigs fed low to adequate levels, J. Nutr. 125 (1995) 2550–2562.

[16] Lobley G.E., Connell A., Revell D.K., Bequette B.J., Brown D.S., Calder A.G., Splanchnic-bed transfers of amino acids in sheep blood and plasma, as monitored through use of a multiple U-13C-labelled amino acid mixture, Br. J. Nutr. 75 (1996) 217–235.

[17] Ortigues I., Durand D., Lefaivre J., Use of para-amino hippuric acid to measure blood flows through portal-drained-viscera, liver and hindquarters in sheep, J. Agr Sci. Camb. 122 (1994) 299–308.

[18] Pico C., Pons A., Palou A., Decrease of the pool of amino acids adsorbed on blood cell membranes caused by starvation in rats, Life Sci. 57 (1998) 675–683.

[19] Proenza A.M., Palou A., Roca P., Amino acid distribution in human blood. A significant pool of amino acids is adsorbed onto blood cell membranes, Biochem. Mol. Biol. Int. 34 (1994) 971–982.

[20] Reeds P.J., Burrin D.G., Jahoor F., Wykes L., Henry J., Frazer E.M., Enteral glutamate is almost completely metabolized in first pass by the gastrointestinal tract of infant pigs, Am. J. Physiol. 270 (1996) E413–418.

[21] Rérat A., Simoes-Nunes C., Mendy F., Vaissade P., Vaugelade P., Splanchnic fluxes of amino acids after duodenal infusion of carbohydrate solutions containing free amino acids or oligopeptides in the non-anaesthetized pigs, Br. J. Nutr. 68 (1992) 111–138.

[22] SAS, SAS user's guide, Version 6.11, SAS Institute Inc., Cary, NC, 1996.

[23] Wahren J., Felig P., Hagenfeldt L., Effect of protein ingestion on splanchnic and leg metabolism in normal man and in patients with diabetes mellitus, J. Clin. Invest. 57 (1976) 987–999.

[24] Windmueller H.G., Spaeth A.E., Intestinal metabolism of glutamine and glutamate from the lumen as compared to glutamine from blood, Arch. Biochem. Biophys. 171 (1975) 662–672.

[25] Windmueller H.G., Spaeth A.E., Respiratory fuels and nitrogen metabolism in vivo in small intestine of fed rats. Quantitative importance of glutamine, glutamate, and aspartate, J. Biol. Chem. 255 (1980) 107–112.

[26] Young J.D., Ellory J.C., Red cell amino acid transport, in: Membrane Transport in Red Cells, Academic Press, 1977, pp. 301–325.