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Associations between piglet umbilical blood hematological criteria, birth order, birth interval, colostrum intake, and piglet survival

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Abstract

A total of 656 pigs (623 live-born and 33 stillborn) from 43 sows were used to evaluate hematological criteria at birth and their association with piglet survival. At birth of each piglet, birth time and order within the litter, weight, umbilical cord status (intact or ruptured) and whether the pig was live-born or stillborn were recorded. A 200µL sample of blood from the umbilical cord was collected and immediately analyzed for concentrations of glucose, oxygen partial pressure (**pO_2**), carbon dioxide partial pressure (**pCO_2**), pH, base excess (**BE**), bicarbonate (**HCO_3**), saturated oxygen (**sO_2**), total carbon dioxide (**TCO_2**), sodium, potassium, ionized calcium (**iCa**), hematocrit (**Hct**), and hemoglobin (**Hb**) on a hand held iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ). Piglets were categorized into quartiles based on birth order and cumulative birth interval (**CumBI**). Live-born pigs had higher ($P < 0.01$) umbilical cord blood pH, HCO_3, BE, sO_2, TCO_2, and birth weight compared with stillborn pigs, but lower ($P < 0.01$) pCO_2, K, iCa, and glucose compared with stillborn pigs. Pigs with intact umbilical cords at birth were associated with higher ($P < 0.01$) blood pH, HCO_3, BE, and TCO_2 compared with piglets born with a ruptured umbilical cord. Pigs with intact umbilical cords were associated with lower ($P < 0.01$) Hct and Hb concentrations and born earlier ($P < 0.01$) in the birth order compared with pigs born with a ruptured umbilical cord. Pigs that did not survive to weaning had lower ($P < 0.01$) umbilical cord blood pH, HCO_3, BE, sO_2, TCO_2, Na, glucose, and birth weight, and 24 hr weight compared with pigs alive at weaning. Pigs born in the first quartile for CumBI had higher ($P < 0.05$) pH compared with pigs in the other three quartiles. Umbilical cord blood HCO_3, BE, and TCO_2 decreased ($P < 0.05$) with each change in CumBI quartile from first to last. Blood glucose was lowest ($P < 0.05$) in pigs born before 44 min and highest in pigs born after 164 min. Umbilical cord blood pH, HCO_3, BE, TCO_2, Na, glucose, Hct, and Hb were positively associated ($P < 0.001$) with colostrum intake, indicating increased blood values resulted in higher colostrum intake. Although a pig may be live-born, their survival to 24 hr and to weaning is reduced when blood pH, HCO_3, BE, and sO_2 are lower reiterating the importance of management practices that can reduce the birth interval between pigs and the number of pigs experiencing moderate to severe hypoxia.

Key words: acid–base balance, birth interval, hematological criteria, hypoxia, piglet survival

Abbreviations

BE	base excess
CumBI	cumulative birth interval
Hb	hemoglobin
HCO_3	bicarbonate
Hct	hematocrit
iCa	ionized calcium
pCO_2	carbon dioxide partial pressure
pO_2	oxygen partial pressure
sO_2	saturated oxygen
TCO_2	total carbon dioxide

Introduction

Fetal hypoxia during parturition is a common event in swine because they are a litter bearing species. Hypoxia is typically considered a cause of stillborn piglets and reduced piglet vitality in the first few hours of life (Alonso-Spilsbury et al., 2005). Many physiological traits with both the sow and piglet have been associated with an increased risk of hypoxia, such as increased farrowing duration, larger litter size, successive uterine contractions, and born later in the birth order (Randall, 1972; Alonso-Spilsbury et al., 2005). The physiological changes occurring in pigs that suffer from fetal hypoxia often include indications of acidosis such as an increase in blood lactate and a concurrent decrease in blood pH.

As litter size continues to increase in modern high-prolific sows, a concurrent increase in farrowing duration has also been observed and is associated with increased stillborn rate (van Dijk et al., 2005; Theil, 2015). Quantifying the effect of birth order and length of parturition on hematological criteria in piglets can help to identify piglets that have experienced hypoxia during the parturition process (Langendijk et al., 2018). Furthermore, understanding the magnitude and relationship between acid–base balance in blood at birth on the piglet's ability to consume colostrum and survive in the first 24 hr after birth and to weaning can help identify sow management or nutritional strategies that can increase piglet survival. Therefore, the objective of the present study was to identify associations between umbilical cord hematological criteria and piglet birth order, birth interval, colostrum intake, and piglet survival.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. This study was conducted on a commercial 3,000-sow farm in southern Minnesota during summer 2019. The facilities were environmentally controlled with mechanical ventilation.

A total of 43 sows (Fast Large White × PIC Landrace) were randomly selected over a 7-wk period to be continuously monitored during farrowing. On day 113 of gestation, sows were moved from gestation stalls into farrowing stalls. Each farrowing stall was equipped with a shelf feeder and nipple drinker for the sows, and a heat mat and nipple drinker for the piglets. Sows were continuously monitored during farrowing for accurate recording of all variables and timely collection of umbilical cord blood. All live and dead full-term piglets were included in the study, whereas mummified fetuses were excluded. Farrowing assistance was given to the sow if the birth interval exceeded 30 to 45 min between piglets. If farrowing assistance resulted in a pulled pig, the sow was "sleeved" again to remove additional pigs.

A total of 683 pigs (638 live-born and 45 stillborn) from 43 sows (parity = 3.9, total born = 15.9) were included in the study. As each piglet was born, birth time, birth order, birth weight, and farrowing assistance (assisted or unassisted) were recorded. The umbilical cord was identified as intact or ruptured (visible signs of breakage due to sow contractions or stretching intrauterine) at birth. A 200-μL sample of mixed venous and arterial blood from the proximal end of the umbilical cord was collected into a lithium heparin tube within 1 min of birth of each pig. Whole blood was immediately analyzed for concentrations of glucose, oxygen partial pressure (**pO_2**), carbon dioxide partial pressure (**pCO_2**), pH, base excess (**BE**), bicarbonate (**HCO_3**), saturated oxygen (**sO_2**), total carbon dioxide (**TCO_2**), sodium, potassium, ionized calcium (**iCa**), hematocrit (**Hct**), and hemoglobin (**Hb**) on a hand held iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ).

After blood collection, all piglets were weighed, individually identified with an ear tag, dried using a desiccant (Techdry; TechMix, LLC, Stewart, MN) and a paper towel, and placed next to the sow's underline. Cumulative birth interval for each pig born was calculated as the time elapsed from the birth of first pig until birth time of the current pig. Piglets were reweighed at 24 hr after birth of the first pig to calculate colostrum intake as described by Theil et al. (2014). Any pig that died prior to 24 hr (n = 69) was assumed to have no colostrum intake. All live-born piglets were followed until weaning, with all removals and mortalities weighed and recorded. At weaning (day 21 ± 2), each piglet was weighed to calculate piglet growth rate.

Statistical analysis

Birth-order ranking was calculated for each pig as: [(pig birth order − 1)/(total born − 1)], as described by van Dijk et al. (2006), where the first pig in each litter would have rank 0, and the last pig would have a ranking of 1. Pigs with a higher number in birth-order ranking means they were born later in the birth order of that litter. Pigs were then categorized into 4 birth-order categories: category 1 ≤ 0.25, 0.25 < category 2 ≤ 0.50, 0.50 < category 3 ≤ 0.75, category 4 > 0.75. Pigs were also categorized according to their birth interval. Cumulative birth interval (**CumBI**) categories were selected based on quartiles of the pig population and were as follows: CumBI ≤ 44 min, 44 <CumBI ≤ 95 min, 95<CumBI ≤ 164, and CumBI > 164.

Data were analyzed using generalized linear mixed models, where pig was the experimental unit, birth type (live-born or stillborn) was the fixed effect, with the random effect of sow. Separate linear mixed models were used to evaluate the fixed effects of umbilical cord status (ruptured or intact), farrowing assistance (unassisted or assisted), birth-order category, CumBI category, pig status at 24 hr (dead or alive), and pig status at weaning (dead or alive). Statistical models were fit using linear models using the Lme function (nlme package of R, version 3.5.2). Residuals of each blood criteria were checked for normal distribution. The blood criteria pCO_2, pO_2, and glucose were not normally distributed therefore they were log transformed for analysis. Multiple mean comparisons were performed with adjustments according to Tukey–Kramer. Univariate linear regression analyses were used for evaluating the association between colostrum intake and umbilical cord hematological criteria or total born. Results were considered significant at $P < 0.05$.

Results

Of the 683 live-born and stillborn pigs, blood samples were unable to be collected from 12 stillborn pigs due to lack of blood in the umbilical cord. In addition, 15 live-born piglets did not produce enough blood to be used in the iStat analyzer and therefore were excluded from analysis. As a result, data were collected from 623 live-born and 33 stillborn piglets (Table 1).

Live-born vs. stillborn

Live-born pigs had higher ($P < 0.01$) umbilical blood pH, HCO_3, BE, sO_2, TCO_2, and birth weight compared with stillborn pigs, whereas stillborn pigs had higher ($P < 0.01$) pCO_2, K, iCa, and glucose compared with live-born pigs (Table 2). There was no evidence for a difference ($P > 0.05$) between live-born or stillborn pigs for pO_2, Hct, or Hb concentrations in umbilical cord blood.

Umbilical cord status

Pigs with intact umbilical cords at birth were associated with higher ($P < 0.01$) pH, HCO_3, BE, and TCO_2 blood concentrations compared with piglets born with a ruptured umbilical cord (Table 3). Piglets with a ruptured umbilical cord were associated with higher ($P < 0.01$) Hct and Hb concentrations and born later ($P < 0.01$) in the birth-order compared with pigs born with an intact umbilical cord. There was no evidence for difference ($P > 0.05$) in blood pCO_2, pO_2, sO_2, Na, K, iCa, glucose, or birth weight between pigs born with an intact or ruptured umbilical cord. Born alive pigs had a lower percentage of pigs born with ruptured umbilical cords compared with stillborn pigs (17.9% vs. 43.1 %).

Farrowing assistance

Of the 656 pigs, 113 pigs (17.2%) were physically assisted out of the birth canal. Pigs that were unassisted had higher ($P < 0.01$) blood pH, pO_2, HCO_3, BE, sO_2, TCO_2, Na, Hct, and Hb compared with piglets that had been assisted (Table 4). Pigs that were assisted had higher ($P < 0.01$) iCa and glucose concentrations compared with piglets that were unassisted. There was no evidence for difference ($P > 0.05$) in umbilical cord pCO_2, K, or birth weight between pigs that were unassisted compared with assisted at birth.

Survival to 24 hr

Of the 623 pigs live-born, 38 (6.1%) were classified as a mortality before 24 hr after birth (Table 5). Pigs that did not survive to 24 hr after birth had lower ($P < 0.01$) blood pH, HCO_3, BE, sO_2, TCO_2, glucose concentrations, and birth weight compared with piglets that were alive at 24 hr. Pigs that survived to 24 hr had lower ($P < 0.01$) pCO_2 and iCa compared with pigs that died in the first 24 hr of life. There was no evidence for difference ($P > 0.05$) between pigs that survived or died in the first 24 hr for pO_2, Na, K, Hct, Hb, or birth order.

Survival to weaning

Of the 623 pigs live-born, 158 (25.3%) were classified as a mortality before weaning (Table 6). Pigs that did not survive to weaning had lower ($P < 0.01$) blood pH, HCO_3, BE, sO_2, TCO_2, Na, glucose, birth weight, and 24 hr weight compared with pigs alive at weaning. Pigs that survived to weaning had lower ($P < 0.01$) iCa compared with pigs that died before weaning. There was no evidence for difference between pigs that survived or died before weaning for pCO_2, pO_2, K, Hct, or Hb.

Table 1. Population statistics of total born piglets[1]

	Mean	Min	Max	NA[2]
Total born[3], *n*	16.9	4	24	0
Stillborn rate[3], %	6.4	0.0	31.3	0
pH	7.43	6.49	7.94	7
pCO_2, mmHg	39.8	9.8	131.0	6
Log pCO_2, mmHg	3.63	2.28	4.88	6
pO_2, mmHg	38	14	191	1
Log pO_2, mmHg	3.75	2.64	5.25	1
HCO_3, mmol/L	25.9	3.7	39.6	11
BE, mmol/L	1.59	−30.0	20.0	12
sO_2, mmol/L	71.4	13.0	100.0	10
TCO_2, mmol/L	27.2	4.0	41.0	13
Na, mmol/L	124.3	99.0	144.0	2
K, mmol/L	7.0	2.8	9.1	21
iCa, mmol/L	1.57	0.65	2.60	1
Glucose, mg/dL	43	19	566	5
Log glucose, mg/dL	3.63	2.94	6.33	5
Hematocrit, % PCV	22.2	14	45	21
Hemoglobin, g/dL	7.6	5.0	13.6	23
Birth weight, g	1,256	290	2,250	0
24 hr weight, g	1,373	310	2,590	69
Wean weight, kg	4.83	1.72	8.12	191

[1]Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed by a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ).
[2]Number of pigs with a value not reported from the iStat portable clinical analyzer, or missing weights due to mortality.
[3]Total born and stillborn rate by sow.

Table 2. Effects of live-born or stillborn on blood criteria[1]

	Live-born	Stillborn	SEM	*P*-value
N	623	33	—	—
pH	7.45	6.98	0.01	<0.001
pCO_2, mmHg	37.0	51.9	—[2]	<0.001
pO_2, mmHg	42.5	42.5	—[3]	0.980
HCO_3, mmol/L	26.5	16.9	0.37	<0.001
BE, mmol/L	2.4	−13.6	0.45	<0.001
sO_2, mmol/L	72.3	54.4	1.29	<0.001
TCO_2, mmol/L	27.6	18.8	0.38	<0.001
Na, mmol/L	124.7	120.5	0.61	0.004
K, mmol/L	6.9	7.8	0.16	0.004
iCa, mmol/L	1.6	1.8	0.03	<0.001
Glucose, mg/dL	38.9	126.1	—[4]	<0.001
Hematocrit, %PCV	22.3	23.5	0.41	0.128
Hemoglobin, g/dL	7.6	8.0	0.13	0.094
Birth weight, g	1,282	1,148	31.4	0.019
Birth-order ranking[5]	0.48	0.80	0.01	<0.001
CumBI[6]	101	178	7.4	<0.001

[1]Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ).
[2]Log transformation used for analysis. Log transformed means were 3.61 and 3.95 for born alive and stillborn, respectively. SEM was 0.02.
[3]Log transformation used for analysis. Log transformed means were 3.75 for born alive and stillborn. SEM was 0.04.
[4]Log transformation used for analysis. Log transformed means were 3.60 and 4.30 for born alive and stillborn, respectively. SEM was 0.03.
[5]Birth-order ranking was calculated for each pig as: [(pig birth order – 1)/(total born – 1)].
[6]Cumulative birth interval for each pig born was calculated as the time (min) elapsed from the birth of first pig until birth time of the current pig.

Table 3. Effects of umbilical cord status at birth on blood criteria[1]

	Intact	Ruptured	SEM	P-value
N	551	105	—	—
Stillborn, n	23	10	—	—
Born alive, n	528	95	—	—
pH	7.44	7.38	0.02	0.013
pCO_2, mmHg	37.7	37.0	—[2]	0.545
pO_2, mmHg	42.1	44.7	—[3]	0.263
HCO_3, mmol/L	26.3	24.7	0.68	0.016
BE, mmol/L	2.1	−0.1	0.91	0.016
sO_2, mmol/L	71.8	70.1	2.32	0.459
TCO_2, mmol/L	27.5	25.9	0.68	0.017
Na, mmol/L	124.4	124.9	0.97	0.567
K, mmol/L	7.0	6.8	0.23	0.495
iCa, mmol/L	1.6	1.6	0.04	0.477
Glucose, mg/dL	43.4	42.5	—[4]	0.470
Hematocrit, %PCV	22.1	23.7	0.58	0.001
Hemoglobin, g/dL	7.5	8.0	0.19	0.005
Birth weight, g	1,278	1,261	43.1	0.617
Birth-order ranking[5]	0.47	0.60	0.03	<<0.001
CumBI[6]	100	133	9.5	<<0.001

[1]Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ).
[2]Log transformation used for analysis. Log transformed means were 3.61 and 3.63 for ruptured and intact, respectively. SEM was 0.04.
[3]Log transformation used for analysis. Log transformed means were 3.80 and 3.74 for ruptured and intact, respectively. SEM was 0.06.
[4]Log transformation used for analysis. Log transformed means were 3.70 and 3.61 for ruptured and intact, respectively. SEM was 0.05.
[5]Birth-order ranking was calculated for each pig as: [(pig birth order − 1)/(total born − 1)].
[6]Cumulative birth interval for each pig born was calculated as the time (min) elapsed from the birth of first pig until birth time of the current pig.

Table 4. Effects of farrowing assistance on blood criteria at birth[1]

	Unassisted	Assisted	SEM	P-value
N	543	113		
pH	7.44	7.37	0.01	<0.001
pCO_2, mmHg	36.2	37.0	—[2]	0.938
pO_2, mmHg	44.7	36.9	—[3]	<0.001
HCO_3, mmol/L	26.4	24.3	0.42	<0.001
BE, mmol/L	2.3	−0.9	0.53	<0.001
sO_2, mmol/L	73.5	62.1	1.28	0.010
TCO_2, mmol/L	27.6	25.5	0.42	<0.001
Na, mmol/L	125.0	121.9	0.63	0.001
K, mmol/L	6.9	6.9	0.16	0.83
iCa, mmol/L	1.6	1.7	0.03	<0.001
Glucose, mg/dL	40.8	55.3	—[4]	<0.001
Hematocrit, %PCV	22.5	21.4	0.41	0.021
Hemoglobin, g/dL	7.6	7.3	0.13	0.036
Birth weight, g	1,269	1,311	32.3	0.215
Birth-order ranking[5]	0.48	0.58	0.01	0.002
CumBI[6]	99	133	7.2	<0.001

[1]Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ).
[2]Log transformation used for analysis. Log transformed means were 3.61 and 3.59 for unassisted and assisted, respectively. SEM was 0.02.
[3]Log transformation used for analysis. Log transformed means were 3.80 and 3.60 for unassisted and assisted, respectively. SEM was 0.04.
[4]Log transformation used for analysis. Log transformed means were 3.61 and 3.81 for unassisted and assisted, respectively. SEM was 0.03.
[5]Birth-order ranking was calculated for each pig as: [(pig birth order − 1)/(total born − 1)].
[6]Cumulative birth interval for each pig born was calculated as the time (min) elapsed from the birth of first pig until birth time of the current pig.

Birth order

As birth-order ranking increased from < 0.25 to > 0.75, blood pH decreased ($P < 0.05$) between each category (Table 7). Pigs in the first birth-order category had lower ($P < 0.05$) pCO_2 compared with pigs in the higher three categories. Partial oxygen was highest ($P < 0.05$) in pigs born in the third birth-order category compared with pigs born in the first 2 categories with pigs in the last category intermediate. Both HCO_3 and BE were similar ($P > 0.05$) in pigs born in the first 2 categories but was decreased ($P < 0.05$) in pigs in the third category, and lowest ($P < 0.05$) in pigs in the fourth category. The $sO2$ was higher ($P < 0.05$) in pigs born in the third category compared with pigs born in the fourth category, with pigs born in the first half of the litter intermediate. Pigs born in birth-order categories 1 and 2 had increased TCO_2 ($P < 0.05$) compared with pigs born in categories 3 and 4. Sodium was higher ($P < 0.05$) in pigs born in the first category compared with those born in the last with the others intermediate. Potassium was higher ($P < 0.05$) for pigs born in the second half of farrowing compared with the first. As birth-order ranking increased, iCa increased ($P < 0.05$) with the highest ($P < 0.05$) iCa observed in pigs born in the fourth category. Glucose concentration was highest ($P < 0.05$) in pigs born in the third category compared with pigs born in the first category, with pigs born in the second category intermediate. Pigs born in the last category of the litter had the highest ($P < 0.05$) blood glucose concentrations. Hemoglobin and Hct were higher ($P < 0.05$) in pigs born in the last category compared with pigs born in the first or third categories, with pigs born in the second category intermediate. Birth weight was heaviest ($P < 0.05$) in pigs born in the last category compared with pigs born in the first 3 categories of the litter.

Cumulative birth interval

Pigs born in the first quartile for CumBI (<44 min) had higher ($P < 0.05$) pH compared with pigs in the other 3 quartiles (Table 8). Pigs born in the second or third quartile (44 to 95 or 95 to 164 min) had higher ($P < 0.05$) pH compared with pigs in the fourth quartile (>164 min). The HCO_3, BE, and TCO_2 decreased ($P < 0.05$) with each change in CumBI quartile from first to last, with the lowest HCO_3, BE and TCO_2 observed in pigs born after 164 min. Pigs born within 44 min had higher ($P < 0.05$) Na compared with pigs born after 95 min, with pigs born between 44 and 95 min intermediate. Pigs born within 44 min had lower ($P < 0.05$) K than pigs born after 164 min, with those born in the middle 2 CumBI quartiles intermediate. Pigs born before 95 min had lower ($P < 0.05$) iCa compared with pigs born after 95 min for CumBI. Blood glucose was lowest ($P < 0.05$) in pigs born within 44 min, compared with pigs born in the third CumBI quartile (95 to 165 min), with pigs in the second quartile (44 to 95 min) intermediate. Pigs born after 164 min had the highest ($P < 0.05$) blood glucose concentrations compared with pigs in the first 3 CumBI quartiles. Pigs born

Table 5. Effects of umbilical cord blood measurements at birth and piglet characteristics on piglet survival to 24 h[1]

	Mortality	Alive at 24 hr	SEM	P-value
N	38	585	—	—
pH	7.35	7.46	0.03	<<0.001
pCO_2	42.5	37.3	—[2]	0.002
pO_2	36.6	42.5	—[3]	0.099
HCO_3, mmol/L	24.2	26.6	0.96	0.011
BE, mmol/L	–1.5	2.7	1.26	0.001
sO_2, mmol/L	63.3	72.9	3.48	0.005
TCO_2, mmol/L	25.4	27.7	0.97	0.014
Na, mmol/L	122.3	124.8	1.41	0.068
K, mmol/L	6.8	6.9	0.32	0.770
iCa, mmol/L	1.7	1.6	0.06	0.018
Glucose, mg/dL	34.9	39.9	—[4]	0.008
Hematocrit, %PCV	22.5	22.3	0.81	0.736
Hemoglobin, g/dL	7.7	7.6	0.26	0.684
Birth weight, g	1,023	1,299	56.9	<<0.001
Birth-order ranking[5]	0.55	0.47	0.05	0.133
CumBI[6]	117	100	13.0	0.134

[1]A total of 623 live-born pigs were used in analysis for survival to 24 h of life. Umbilical cord blood was collected from a total of immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ).
[2]Log transformation used for analysis. Log transformed means were 3.80 and 3.59 for mortality and alive at 24 hr, respectively. SEM was 0.05.
[3]Log transformation used for analysis. Log transformed means were 3.60 and 3.79 for mortality and alive at 24 hr, respectively. SEM was 0.09.
[4]Log transformation used for analysis. Log transformed means were 3.50 and 3.61 for mortality and alive at 24 hr, respectively. SEM was 0.06.
[5]Birth--order ranking was calculated for each pig as: [(pig birth order – 1)/(total born – 1)].
[6]Cumulative birth interval for each pig born was calculated as the time (min) elapsed from the birth of first pig until birth time of the current pig.

within the first 44 min were lighter ($P < 0.05$) compared with pigs born after 95 min, with pigs born between 44 and 95 min intermediate. There was no evidence ($P > 0.05$) for CumBI to influence pCO_2, pO_2, sO_2, Hct, or Hb.

Colostrum intake associations

Total born was negatively associated ($P < 0.001$) with colostrum intake, as pigs in large litters consumed less colostrum than pigs in small litters (Table 9). Umbilical cord blood pH, HCO_3, BE, TCO_2, Na, glucose, Hct, and Hb were positively associated ($P < 0.001$) with colostrum intake. There was no evidence ($P < 0.001$) for association between pCO_2, pO_2, sO_2, or K and colostrum intake.

Discussion

Mean hematological criteria collected on piglets using the iStat portable analyzer were similar to previous values (Rootwelt et al., 2012; van den Bosch et al., 2019). Litter size of previous studies ranged from 11.7 to 15.9 and average sow parity ranged from 2.0 to 4.2. Sows used in previous studies were Landrace × Yorkshire, Landrace × Large White, or purebred Landrace.

Table 6. Effects of umbilical cord blood measurements at birth and piglet characteristics on survival to weaning[1]

	Mortality	Weaned	SEM	P-value
N	158	465		
pH	7.40	7.47	0.01	<0.001
pCO_2, mmHg	37.7	36.6	—[2]	0.279
pO_2, mmHg	42.1	42.5	—[3]	0.899
HCO_3, mmol/L	24.5	27.1	0.53	<0.001
BE, mmol/L	–0.31	3.31	0.67	<0.001
sO_2, mmol/L	68.7	73.5	1.94	0.010
TCO_2, mmol/L	25.8	28.2	0.55	<0.001
Na, mmol/L	122.8	125.3	0.83	0.001
K, mmol/L	6.93	6.89	0.20	0.822
iCa, mmol/L	1.63	1.54	0.04	0.003
Glucose, mg/dL	36.6	40.1	—[4]	<0.001
Hematocrit, %PCV	22.3	22.3	0.51	0.984
Hemoglobin, g/dL	7.6	7.6	0.17	0.946
Birth weight, g	1,052	1,355	35.9	<0.001
24 hr weight, g	1,101	1,469	41.6	<0.001
Birth-order ranking[5]	0.50	0.47	0.024	0.343
CumBI[6]	107	99	8.7	0.225

[1]A total of 623 live-born pigs were used in analysis for survival to wean. Umbilical cord blood was collected from a total of immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ).
[2]Log transformation used for analysis. Log transformed means were 3.63 and 3.60 for mortality and weaned, respectively. SEM was 0.03.
[3]Log transformation used for analysis. Log transformed means were 3.74 and 3.75 for mortality and weaned, respectively. SEM was 0.05.
[4]Log transformation used for analysis. Log transformed means were 3.53 and 3.64 for mortality and weaned, respectively. SEM was 0.04.
[5]Birth-order ranking was calculated for each pig as: [(pig birth order – 1)/(total born – 1)].
[6]Cumulative birth interval for each pig born was calculated as the time (min) elapsed from the birth of first pig until birth time of the current pig.

While populations varied in the previous studies are spread over several years (van Dijk et al., 2006; Rootwelt et al., 2012; Langendijk et al., 2018; van den Bosch et al., 2019), the range in total born, sow parity, and genetics would be similar to the population of the current study.

Birth status

Intrapartum death resulting in stillborn or mummified fetuses accounts for 9.8% of total born pigs (Stalder, 2018). While mummified fetuses are typically caused from disease, the majority of stillborn pigs occur during the parturition process due to oxygen deprivation (Randall, 1972). Friendship et al. (1990) evaluated cesarean records from 827 sows and observed 2% to 3% of stillborn pigs were unable to be prevented. Several studies have focused on the acid–base balance of piglet blood and identified that pigs which experience asphyxia during parturition are identifiable by decreased blood pH and pO_2, increased lactate, glucose, and pCO_2 concentrations (Alonso-Spilsbury et al., 2005; Mota-Rojas et al., 2012; Rootwelt et al., 2012; Langendijk and Plush, 2019). These changes to the acid–base balance are largely due to interruption of oxygen delivery to the fetus during parturition resulting in respiratory acidosis as fetal CO_2 and H_2CO_3 increase, reducing blood pH and shifting toward anaerobic metabolism. This metabolic shift increases lactic acid production further reducing pH, ultimately ending in metabolic acidosis and intrapartum

Table 7. Effects of birth-order ranking category on umbilical cord blood measurements at birth[1,2]

	Birth order ranking category					
	<0.25	0.25 to 0.50	0.51 to 0.75	>0.75	SEM	P-value
n	182	162	147	165	—	—
pH	7.52[a]	7.46[b]	7.41[c]	7.31[d]	0.02	<0.001
pCO_2, mmHg	34.5[b]	37.7[a]	37.7[a]	40.4[a]	—[3]	<0.001
pO_2, mmHg	40.9[b]	40.0[b]	47.5[a]	42.1[ab]	—[4]	0.007
HCO_3, mmol/L	28.4[a]	27.3[a]	24.9[b]	23.1[c]	0.53	<0.001
BE, mmol/L	5.3[a]	3.5[a]	0.2[b]	–2.7[c]	0.68	<0.001
sO_2, mmol/L	72.9[ab]	70.6[ab]	75.0[a]	67.8[b]	1.80	0.012
TCO_2, mmol/L	29.4[a]	28.5[a]	26.1[b]	24.5[b]	0.53	<0.001
Na, mmol/L	125.6[a]	125.2[ab]	123.8[ab]	123.1[b]	0.78	0.01
K, mmol/L	6.7[b]	6.6[b]	7.3[a]	7.3[a]	0.19	<0.001
iCa, mmol/L	1.47[c]	1.54[bc]	1.61[ab]	1.67[a]	0.03	<0.001
Glucose, mg/dL	35.9[c]	37.4[bc]	45.6[b]	55.4[a]	—[5]	<0.001
Hematocrit, %PCV	21.8[b]	22.3[ab]	21.9[b]	23.4[a]	0.49	0.002
Hemoglobin, g/dL	7.4[b]	7.6[ab]	7.5[b]	8.0[a]	0.16	0.001
Birth weight, g	1,222[b]	1,248[b]	1,268[b]	1,372[a]	36.8	<0.001
CumBI[6]	31[d]	87[c]	129[b]	180[a]	7.6	<0.001

[1]Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ).
[2]Birth-order ranking was calculated for each pig as: [(pig birth order – 1)/(total born – 1)].
[3]Log transformation used for analysis. Log transformed means were 3.54, 3.63, 3.63, and 3.70 for the birth-order categories <0.25, 0.25 to 0.50, 0.51 to 0.75 and >0.75, respectively. SEM was 0.03.
[4]Log transformation used for analysis. Log transformed means were 3.71, 3.69, 3.86, and 3.74 for the birth-order categories <0.25, 0.25 to –0.50, 0.51 to 0.75, and > 0.75, respectively. SEM was 0.05.
[5]Log transformation used for analysis. Log transformed means were 3.55, 3.58, 3.69, and 3.81 for the birth-order categories <0.25, 0.25 to 0.50, 0.51 to 0.75 and > 0.75, respectively. SEM was 0.04.
[6]Cumulative birth interval for each pig born was calculated as the time (min) elapsed from the birth of first pig until birth time of the current pig.

Table 8. Effects of cumulative birth interval category on umbilical cord blood criteria at birth[1,2]

	Cumulative birth interval, min					
	<44	44 to –95	95 to –164	>164	SEM	*P*-value
n	167	161	165	163		
pH	7.52[a]	7.46[b]	7.41[b]	7.32[c]	0.02	<0.001
pCO_2, mmHg	35.5	37.7	38.5	38.9	—[3]	0.061
pO_2, mmHg	42.5	41.3	41.3	44.7	—[4]	0.473
HCO_3, mmol/L	28.8[a]	26.9[b]	25.3[c]	22.7[d]	0.56	<0.001
BE, mmol/L	5.7[a]	3.0[b]	0.6[c]	–2.9[d]	0.75	<0.001
sO_2, mmol/L	74.5	71.3	70.1	69.9	1.90	0.199
TCO_2, mmol/L	29.8[a]	28.1[b]	26.5[c]	24.1[d]	0.56	<0.001
Na, mmol/L	126.1[a]	125.4[ab]	123.6[bc]	122.6[c]	0.80	0.001
K, mmol/L	6.5[b]	6.9[ab]	7.0[ab]	7.4[a]	0.19	<0.001
iCa, mmol/L	1.47[b]	1.52[b]	1.62[a]	1.68[a]	0.04	<0.001
Glucose, mg/dL	34.9[c]	39.9[bc]	48.1[b]	51.5[a]	—[5]	<0.001
Hematocrit, %PCV	22.4	21.9	22.3	22.7	0.51	0.547
Hemoglobin, g/dL	7.6	7.5	7.6	7.7	0.16	0.624
Birth weight, g	1,215[b]	1,252[ab]	1,319[a]	1,329[a]	39.3	0.007

[1]Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ).
[2]Cumulative birth interval for each pig born was calculated as the time (min) elapsed from the birth of first pig until birth time of the current pig.
[3]Log transformation used for analysis. Log transformed means were 3.57, 3.63, 3.65, and 3.66 for the cumulative birth interval categories <44, 44 to 95, 95 to 164 and > 164, respectively. SEM was 0.03.
[4]Log transformation used for analysis. Log transformed means were 3.75, 3.72, 3.72, and 3.80 for the cumulative birth interval categories <44, 44 to 95, 95 to 164 and >164, respectively. SEM was 0.05.
[5]Log transformation used for analysis. Log transformed means were 3.52, 3.60, 3.69, and 3.81 for the cumulative birth interval categories <44, 44 to 95, 95 to 164 and >164, respectively. SEM was 0.04.

Table 9. Univariate associations between colostrum intake and umbilical cord hematological criteria or total born[1,2]

Response	*r*	*P*-value
Total born	−0.38	<0.001
pH	0.20	<0.001
pCO_2[3]	−0.02	0.640
pO_2[3]	−0.03	0.510
HCO_3	0.27	<0.001
BE	0.25	<0.001
sO_2	0.06	0.140
TCO_2	0.26	<0.001
Na	0.16	<0.001
K	−0.01	0.860
iCa	−0.09	0.029
Glucose[3]	0.01	0.019
Hct	0.09	0.024
Hb	0.10	0.021

[1]Umbilical cord blood was collected from a total of 656 piglets (623 live-born and 33 stillborn pigs) from 43 sows (Fast Large White × PIC Landrace) immediately after birth and analyzed in a handheld iStat portable clinical analyzer (iStat Alinity, Abbott Point of Care Inc., Princeton, NJ).
[2]Colostrum intake in 24 hr was calculated using the equation from Theil et al. (2015).
[3]Log transformed values were used.

death of the fetus (Alonso-Spilsbury et al., 2005). This cascade of events was observed in our present study as stillborn pigs had increased CO_2 and reduced pH, BE, and sO_2 compared with live-born pigs. Hypoxia can also disrupt cell membranes and decrease ATPase, Na, and K, which is supported by the decreased Na and increased K observed in blood of stillborn pigs (Alonso-Spilsbury et al., 2005). Furthermore, glucose concentrations in blood will increase during times of stress due to the activation of the sympathetic nervous system initiating glycogenolysis. In general, piglet blood glucose at birth is relatively low (<50 mg/dL) and in fact increased blood glucose measured at birth is not a sign of ability to adapt to extra-uterine life but another indicator of hypoxia during parturition (Herpin et al., 1996).

Signs of asphyxia defined as a decrease in blood acid–base balance are also indicators of postnatal survival (Herpin et al., 1996; Tuchscherer et al., 2000; Mota-Rojas et al., 2005; Langendijk et al., 2018). It has been estimated that 14% to 20% of live-born piglets are asphyxiated at birth (Mota-Rojas et al., 2012; Langendijk and Plush, 2019). Langendijk et al. (2018) evaluated lactate concentration at birth, as an indirect asphyxia indicator. They observed a reduction in day 7 survival of piglets as lactate concentration increased from <3.6 to > 6.40 mmol/L. The authors also observed decreased piglet gain during lactation in pigs born with increased lactate concentrations, but this was confounded with birth weight where pigs with high lactate also had the lowest birth weight (Langendijk et al., 2018). The present study indicated that the population of pigs alive at 24 hr and at weaning had improved umbilical cord blood pH, BE, sO_2, and glucose at birth and heavier birth weights compared with pigs recorded as a mortality. This suggests management practices around or during parturition to improve blood parameters, such as manual assistance for piglets lodged in the birth canal (Kirkden et al., 2013) and targeted piglet management protocols such as split suckling may increase piglet survival.

Colostrum intake

Tuchscherer et al. (2000) identified pigs that survived to day 10 of life were associated with reduced time from birth to first suckle (27 vs. 54 min). Herpin et al. (1996) observed a delayed time to contact the udder in pigs with increased lactate concentration at birth, which is a disadvantage for colostrum consumption. In support of this, Langendijk et al. (2018) observed decreased colostrum intake in piglets that experienced asphyxia during parturition. Our data would concur with these results, as decreases in umbilical cord blood pH, pCO_2 and HCO_3 were associated with decreased colostrum intake. Ultimately, these results suggest piglets with a shorter time to contact the udder and increased vigor at birth will have increased colostrum intake and increase survival to weaning (Panzardi et al., 2013; Ferrari et al., 2014).

Umbilical cord morphology

Several studies have documented the morphology of umbilical cord in relation to piglet vitality at birth (Randall, 1972; Herpin et al., 1996; van Dijk et al., 2006). An observed risk of mortality has been found when a ruptured cord is present at birth compared with umbilical cords that are intact (Herpin et al., 1996). A ruptured cord can be caused by increased contractions with oxytocin use, repeated contractions experienced by pigs born later in the birth order, or twisting of the umbilical cord while moving through the birth canal (Mota-Rojas et al., 2005). Langendijk et al. (2018) observed pigs born with ruptured umbilical cords had more signs of asphyxia, as evidenced by lower pH and increased blood lactate concentrations, compared with piglets with intact umbilical cords at birth. In the present study, lower pH and BE were observed in pigs with ruptured umbilical cord indicating signs of hypoxia as a result of reduced blood flow were beginning intrapartum, which supports previous findings that ruptured umbilical cords are a risk factor for intrapartum death or reduced survival during lactation.

Birth-order and cumulative birth interval

The continual increase in litter size from genetic selection has concurrently increased farrowing duration, which increases the risk of metabolic acidosis and hypoxia due to extended parturition (Vanderhaeghe et al., 2013; Feyera et al., 2018). As the pig spends longer time in utero during farrowing, the pig is exposed to more contractions which can result in reduced oxygen supply or damage to the umbilical cord (Alonso-Spilsbury et al., 2005; van Dijk et al., 2006). Studies have demonstrated that as pigs are born later in the birth order, pH and BE in umbilical cords were decreased and lactate concentration increased indicating pigs born later were experiencing acidosis (Herpin et al., 1996; Langendijk et al., 2018).

van Dijk et al. (2006) categorized CumBI into 3 classes (first, middle, or last third of farrowing) and observed a decrease in piglet blood pH, HCO_3, and BE, and an increase in pCO_2 as pigs was born later after a longer CumBI. In the present study, the CumBI quartiles further quantify the changes in acid–base balance begins as early as 45 min after the onset of parturition, but are exponentially increased in pigs born after 164 min. Furthermore, we identified pigs born later in the birth order also had heavier birth weights. Rootwelt et al. (2012) also documented that a heavier birth weight, placental weight, and placental area were observed for pigs born in the last third of the litter. While birth order and birth weight may be confounded, it is interesting to note that heavier pigs are observed near the end of the birth order where the stillborn rate is increased. It could be hypothesized that heavy pigs at the end of the birth order may increase dystocia in sows, resulting in increased stillborn rate or prolonged farrowing duration. In future research, it will be important to measure both birth-order ranking and the CumBI because while birth order cannot be changed by management practices, the CumBI can be controlled to an extent by farrowing assistance. Therefore, we hypothesize that interventions reducing the birth interval for the later born piglets may improve blood parameters and reduce stillbirth risk.

Summary

In conclusion, the present data are the first to evaluate the association between umbilical cord blood criteria and colostrum intake, and further quantify the magnitude of change in piglet umbilical cord hematological criteria as cumulative birth interval and birth order increases. Our data support the changes in umbilical cord acid–base balance as an indicator for hypoxia with an increase in cumulative birth interval, especially in pigs experiencing parturition longer than 164 min. Furthermore, the present study validates previous data on changes in umbilical cord blood acid–base balance and glucose between live-born and stillborn pigs, and pigs with ruptured umbilical cords at birth. Although a pig may be live-born, it's survival to 24 hr and to weaning is characterized by low blood pH, HCO_3, BE, and sO_2 reiterating the importance of management practices that can reduce the birth interval between pigs and the number of pigs experiencing moderate–to-severe hypoxia.

Conflict of interest statement

The authors declare no real or perceived conflicts of interest.

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