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Genetic and environmental determinants of Immunoglobulin G in kid serum and adult colostrum of dairy goats

M. Wicki,^{1,2} T. Fassier,³ C. Huau,¹ F. Corbière,⁴ and R. Rupp^{1*}

¹GenPhySE, Université de Toulouse, INRAE, ENVT, 31326, Castanet Tolosan, France

²Institut de l'Élevage, Castanet-Tolosan 31321, France

³Domaine de Bourges, INRAE, Osmoy, F-31326, France

⁴IHAP, Université de Toulouse, INRAE, INPT, ENVT, Toulouse, France

ABSTRACT

Immune competence is a key factor in the health and resilience of dairy ruminants. The aim of this study was to study immunoglobulin G concentration in serum shortly after birth and in colostrum of lactating animals as proxy of passive immune transfer and colostrum quality, respectively, and thus provide new health and resilience indicators for selection.

Data from 424 female kids and 203 primiparous goats, reared on an INRAE experimental farm, were analyzed. IgG concentration was measured in kid serum and goat colostrum, respectively, using the radial immunodiffusion technique. Linear models were used to identify factors of variation in serum and colostrum IgG concentration, and health events were monitored for 5 weeks after birth to measure the impact of passive immune transfer on kids' health. We found a significant effect of serum IgG level on hindquarters cleanliness score (as a proxy of digestive troubles) and nasal and ocular discharge. As expected, the absorption of IgG in the days following birth is essential to ensure the passive transfer of immunity from the mother to the youngster, and provide immune protection. Genetic parameters were estimated for serum IgG concentration in kids and for colostrum characteristics in primiparous goats. Heritability of serum IgG in kids was not significantly different from zero. This low value, with large SE, may be due to the limited sample size and large environmental variability likely not accounted for. Especially, we could not adjust for the amount of IgG that was ingested by the kid, which can have a significant effect on serum IgG and possibly on heritability estimates. Heritability of colostrum traits were moderate, with estimates of 0.25 (± 0.16), 0.35 (± 0.16), and 0.25 (± 0.16) for IgG concentration, IgG mass and colostrum volume, respectively. Genetic correlations with milk

production showed high standard errors due to small numbers. However, estimates suggest a negative genetic association between production and IgG concentration in colostrum ($rg = -0.44 \pm 0.33$), probably linked to a positive association with total colostrum volume. The significant heritabilities that were estimated for the first time demonstrate the existence of genetic control of colostrum quality in goats, and open up opportunities for selection in this species.

Key Words: immunoglobulins, colostrum, passive immune transfer, genetic parameters, dairy goats

INTRODUCTION

The development of integrated management practices aimed at improving animal health is an essential pillar in the adaptation of livestock farming to global changes and the agroecological transition of livestock system (Mottet et al., 2020). The contribution of genetics has proven successful to improve resistance to specific infectious diseases such as mastitis in dairy cattle (Heringstad et al., 2000) or gastrointestinal parasitism in sheep (Moreno-Romieux et al., 2017). Another strategy is to incorporate immunocompetence criteria into breeding programs (Mallard et al., 2015). Much knowledge remains to be acquired on this approach, however, and links between immunocompetence, genetic resistance and welfare should be more systematically and accurately studied (Ducos et al., 2021).

Among the components of ruminant resistance and health, survival in early life is a key element. In some situations, the mortality rate during this period can be very high (O'Brien and Sherman, 1993). In ruminants, the young are born virtually agammaglobulinemic due to the synepitheliochorial placenta, therefore protection from infectious diseases mostly depends on the quality of passive immunity transfer (TPI) from colostrum (Borghesi et al., 2014). Compared with milk, colostrum is characterized by a higher protein content, particularly of various types of immunoglobulins. It is also richer in lipids, vita-

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*Corresponding Author: Rachel Rupp rachel.rupp@inrae.fr

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mins, minerals, trace elements, enzymes and hormones, which may act as non-immunoglobulin immune factors and participate to thermoregulation (Blum and Hammon, 2000; Silva and Bittar, 2019; Fischer-Tlustos et al., 2021). Immunoglobulins (Ig) form an important component of the immunological activity found in colostrum and are central to the transfer of passive immunity (Hurley and Theil, 2011). In ruminants, it has long been established that the health of the young depends to a large extent on the quality of passive immunity transfer, which relies on the ingestion of sufficient quality colostrum shortly after birth (O'Brien and Sherman, 1993; Christley et al., 2003; Dwyer et al., 2016; Lombard et al., 2020; Sutter et al., 2023). Besides lowering the risk of preweaning morbidity and mortality, successful transfer of passive immunity in calves might also bring long-term advantages such as increased postweaning survival, enhanced growth rate or improved milk production in the first and second lactations (Robison et al., 1988; DeNise et al., 1989).

A few studies have estimated significant heritability for IgG concentration in adult colostrum and newborn serum in sheep (Gilbert et al., 1988) and cattle (Conneely et al., 2013; Soufleri et al., 2019; Martin et al., 2021; Cordero-Solorzano et al., 2022) which assess genetic control of the host. In goats, however, little is known about the Ig concentrations in kid serum or female colostrum, and no information is available on their genetic control and selection opportunities.

Accordingly, the aims of this study were to: i) study serum Ig concentrations in newborn kids and its link with health in early life, ii) measure colostrum quality including Ig concentration and explore interindividual variability and factors of variation and iii) estimate genetic parameters for latter colostrum and serum traits. The hypothesis was that these traits have sufficient genetic variability to allow genetic improvement.

MATERIALS AND METHODS

The experiment was carried out in agreement with French National Regulations for the humane care and use of animals for research purposes. Animals were bred at the experimental INRAE Farm (La Sapinière, Osmoy, France, experimental approval: C18-174-01). The experimental approval was APAFIS#8613-2017012013585646 V4.

ANIMALS

Data came from 424 female kids and 203 primiparous lactating Alpine goats, reared at the experimental INRAE Farm (La Sapinière, Osmoy, France). Birth year of daughters in the experiment ranged from 2017 to 2021 and goats were monitored until 2021. A total of 177 goats were measured both as kids and lactating goats.

All goats were managed identically indoors all year round in the same facility. At the age of 2 mo all replacement goat kids were treated against coccidiosis (Toltrazuril, Baycox®, Elanco) and vaccinated against Q fever at the age of 4 mo (Coxevac®, Ceva Animal Health). Goats were inseminated at about 7 mo of age. Kidding occurred between January and early February each year. Before kidding, the goats were placed in individual pens, to facilitate monitoring by the farm staff. Immediately after birth, the kids were separated from their dam to avoid under-the-dam colostrum intake and reduce the risk of transmission of Caprine Arthritis Encephalitis Virus. Kids were bottle-fed with 300 mL of pooled, heat-treated colostrum (56°C for 1 h) collected from several goats kidding at the same time. Until weaning at around 10 weeks of age, with a live weight of 17 kg, the kids were placed in collective pens to form batches of around 15 individuals. These batches were reconstituted each week according to the weight of the kids, to limit competition, particularly for access to food. Feeding was carried out via an automatic feeder providing continuous access to freshly reconstituted milk.

Lactating goats were milked twice a day at 7 a.m. and 3:30 p.m. with a DeLaval milking machine (DeLaval France) in a Rotolactor parlor (Eurl Gabard Systeme) from February to October (with milk withdrawal period of 1 week after kidding). Goats were then dried off for 3 mo.

ASSESSMENT OF IMMUNOGLOBULIN CONCENTRATION IN SERUM AND COLOSTRUM, AND OTHER COLOSTRUM TRAITS

The quality of transfer of passive immunity in kids was assessed by measuring their serum IgG concentration within the first week of life. Between 1 and 8 d of age whole blood was collected from kids by jugular venipuncture into vacuum tubes without anticoagulant. Only one blood sample was collected per kid. Blood samples were refrigerated for 4 h before serum was separated by centrifugation, with one aliquot being immediately frozen at -20°C until analysis.

In 2018 and 2019, colostrum was collected from each goat using a milking jar for the 2 first milkings: the first one occurred on average 2 h and 10 min (maximum +6 h) after parturition and on average 12h and 50 min (maximum +24 h) after parturition for the second milking. At each milking, the colostrum collected was weighed and converted into a proxy of volume (Vcolostrum) using a density of 1.048. A representative 40 mL colostrum sample of each milking was frozen at -20°C until analysis. Following preliminary analysis in 2018 and 2019, only the first milking after parturition was collected and analyzed in 2020 and 2021.

Immunoglobulin G1 concentrations in kid serum (serum[IgG]) and goat colostrum (colostrum[IgG]) were assessed using a commercial radial immunodiffusion assay (RID) (Sheep and Goat IgG IDRing, GTP Immuno) at the Agrolab laboratory (Auch, France). The assay was performed on total colostrum. For each series of assays, 4 standard calibration samples were included. Readings were taken using IDRing® Viewer and concentration results obtained using IDRing® Meter software (GTP Immuno, Issoire, France). Milk fat in colostrum was estimated by the gold standard acid-butyrometric method (Gerber method, ISO 19662 | FIL 238:2018). All analyses were carried out within 5 mo of sample collection. The only exception was for the serum IgG samples collected in the first year (2017) which were analyzed only the year after (2018). For each colostrum sample, colostrum [IgG] was multiplied by Vcolostrum to obtain the total amount of IgG delivered in colostrum (colostrum IgG mass).

HEALTH ASSESSMENT IN EARLY LIFE

Kidding date and hour, kidding difficulties, kid weight, and litter size were recorded by the farm staff. The kid's vigor at birth, evaluated on average at 2.11 (± 0.59), was scored as follows: 1: lying down with few or no movement; 2: standing and staggering; 3: standing and able to move with confidence. Time to complete ingestion of colostrum was also recorded and, in most cases (81%), was less than 3 h.

From birth to 5 weeks of age, each kid was clinically evaluated by trained farm personnel on a weekly basis, based on the following criteria: hindquarters cleanliness score (1: clean/2: fecal matter visible when tail is lifted/3: fecal matter visible on the peripheral area of the tail), presence of diarrhea (0/1), presence of nasal discharge (0/1), presence of eye discharge (0/1), breathing difficulties (0/1) and rectal temperature (until 2020). This 5-week limit was chosen following earlier observations made on the experimental farm, which showed that the vast majority of health disorders in kids occurred during this period. Rectal temperature was considered abnormal if not between 37.5°C and 39.5°C. However, in our study, we did not detect any temperature below 37.5°C. Therefore, rectal temperature was transformed into a binary variable to distinguish normal temperatures from temperatures above the 39.5°C threshold (0/1).

We further combined the observation of binary records from the 5 weeks observations as follows: the value 0 corresponded to the event “no occurrence of the phenomenon over the first 5 weeks,” while the value 1 corresponded to the event “there was at least one occurrence of the phenomenon over the 5-week observations.” The presence of diarrhea, nasal and eye discharge, and

abnormal rectal temperature was considered as a binary trait, rather than considering the number of occurrences of each disorder, because when a disorder was present, it generally only appeared once during the measurement period. Finally, for the hindquarters cleanliness score, the variable studied was the sum of the squared cleanliness scores over the first 5 observations. The resulting variable lied within the interval [5,45]. After further log-transformation the hindquarters cleanliness score was continuously distributed.

MILK PRODUCTION IN LACTATING GOATS

Milk yield was measured every 3 weeks in first lactation, as part of the official milk records for the herd. Milk yield was analyzed for 390 primiparous goats from the same herd and study years. Total milk was calculated with Fleishmann method using test day records of 250 DIM (MY250) lactation period (Ruiz et al., 2000).

STATISTICAL ANALYSES

Logarithmic transformation was applied to all serum and colostrum variables (i.e., serum [IgG], colostrum IgG mass, colostrum [IgG] and Vcolostrum) before statistical analysis to normalize the distribution of the data. A few extreme values (± 3 standard deviations; $n = 5, 6, 5$ and 8 for serum [IgG], colostrum [IgG], colostrum IgG mass and Vcolostrum, respectively) were excluded from subsequent analyses.

Ancova Linear models with normally distributed residuals were fitted to identify and quantify the factors associated with serum [IgG] and colostrum traits. For serum [IgG], the tested fixed effects were: year of birth of the kid (5 classes: 2017 to 2021), birth weight of the kid (kg, continuous), time interval between birth and blood sampling (1–8 d, continuous), litter size in which the kid was born (3 classes: 1, 2 and ≥ 3), kid's vigor at birth (3 classes, see above), time to complete colostrum intake (3 classes: ≤ 3 h, 3–6h, ≥ 6 h) and parity of the dam (3 classes: 1, 2 and ≥ 3).

For colostrum traits, i.e., colostrum [IgG], IgG mass and Vcolostrum, the tested fixed effects were: year of measurement (4 classes: 2018 to 2021), litter size of the kidding event (2 classes: 1 or ≥ 2) and time from kidding to colostrum sampling (minutes, continuous).

Logistic models were fitted to investigate the associations between serum [IgG] and kid's health. The dependent variables studied were the binary assessment (0 or at least 1 occurrence) during the first 5 weeks of life, of the presence of diarrhea, nasal discharge, eye discharge, breathing difficulties and abnormal rectal temperatures. In addition to serum [IgG], the model included the previously described effects: year of birth of the kid, litter

size, birth weight and vigor at birth. As the hindquarter's cleanliness score was continuously distributed, its association with serum [IgG] was assessed using a linear model with the same independent variables.

All models were fitted using the *lm* and *glm* functions in R software (version 4.2.2; (R Core Team (2021))). Statistical significance was defined when the *p* value was smaller than 0.10 and the results meeting this criterion were discussed. The *p* values were based on type III Sum of Squares.

Estimation of Genetic Parameters Estimates of variance components of TPI, colostrum traits and MY250, were obtained by restricted maximum likelihood (REML) using the Wombat software (Meyer, 2007). For all traits, only one record per animal was available. MY250 was analyzed for 390 primiparous goats from the same herd and study years. Out of 203 primiparous goat, 195 had also a record for MY250. Univariate analyses were performed to obtain heritabilities, using mixed models including fixed effects selected from preliminary ancova.

For serum [IgG], the model was of the following form

$$y = X\beta + Z\alpha + Zc + \epsilon,$$

Where, *y* is the vector of observations; *β* is the vector of fixed effect; *α* and *c* are the vectors of solutions for the coefficients of direct animal (additive) genetic effects and the permanent environmental effect of the dam; *ε* is the vector of residual effects; and *X*, *Za*, and *Zc* are incidence matrices of these effects, respectively. The fixed effects were birth year, time interval between parturition and colostrum sampling, and parity of the dam. A direct genetic maternal effect could not be implemented because of the structure of the data and limited sample size. The data set included a total of 289 different dams, with an average of 1.47 recorded female kids per dam.

For colostrum traits (colostrum IgG mass, colostrum [IgG], Vcolostrum) and MY250 the model was of the following form:

$$y = X\beta + Z\alpha + \epsilon,$$

Where, *y* is the vector of observations; *β* is the vector of fixed effect; *α* is the vector of solutions for the coefficients of direct animal (additive) genetic effects; *ε* is the vector of residual effects; and *X* and *Z* are incidence matrices. For colostrum traits, the fixed effects were year of measurement, litter size and time interval between birth and blood sampling. For MY250, the fixed effects were year of measurement, litter size and age at kidding (2 classes).

The pedigree matrix traced family relationships over 5 generations and included between 1030 and 1474

individuals depending on the number of animals with phenotypes.

Bivariate analyses were then carried out to obtain correlations between pairs of traits for MY250 and colostrum traits.

We declared heritability or genetic correlation to be significant when the estimate ± 1 standard error did not include 0.

RESULTS

Descriptive statistics

Descriptive statistics for serum IgG traits in female kids are summarized in Table 1. The mean serum [IgG] of kids between 1 and 8 d of age was 8.20 ± 5.87 g/L. Based on thresholds proposed for calves (Godden et al., 2019), the transfer of passive immunity was considered to be poor (serum [IgG] < 10 g/L) for 304 kids (71.7%), fair (serum [IgG]: 10–17.9 g/L) for 93 (21.9%), good (serum [IgG]: 18–24.9 g/L) for 19 kids (4.5%) and excellent (serum [IgG] ≥ 25 g/L) for the 8 remaining kids (1.9%). Logarithmic transformation was used to normalize data distributions (Figure 1).

Descriptive statistics for colostrum traits in adult goats are summarized in Table 2 and Table 3.

The average colostrum volume was 1.08 L at first milking and 0.71 L at second milking in the preliminary data set collected in 2018–2019 (*n* = 101; Table 2). The total colostrum volume was therefore on average 1.8 L during the first 24 h when collected exhaustively after parturition. Correlation between first and second milking for volume, IgG concentration and fat content were *r* = 0.40 (*P* = < 0.0001), *r* = 0.28 (*P* = 0.0056), and *r* = 0.23 (*P* = 0.0231) respectively.

Correlation between first and second milking for IgG mass was not significantly different from zero (*r* = -0.015, *P* = 0.8781). Correlation of fat content with colostrum volume and mass were small, e.g., -0.16 (*P* = 0.0214) and -0.15 (*P* = 0.0299), respectively, and not significantly different from zero for IgG concentration (*r* = -0.004, *P* = 0.0518). IgG mass was much lower in the second milking (17.3 ± 18.2 g) than in the first milking (43.3 ± 26.2 g). For a few goats (*n* = 13), the exact time of parturition was not observed and was estimated by the technicians; this did not affect the ranking of IgG mass and concentration. Following these preliminary results obtained in 2018 and 2019, and given that only colostrum from the first milking is distributed to the kids, only the first milking was collected and analyzed in subsequent years (2020 and 2021).

Table 3 summarizes statistics on the characteristics of colostrum, collected only during the first milking, over the entire period from 2018 to 2021 (*n* = 203 ob-

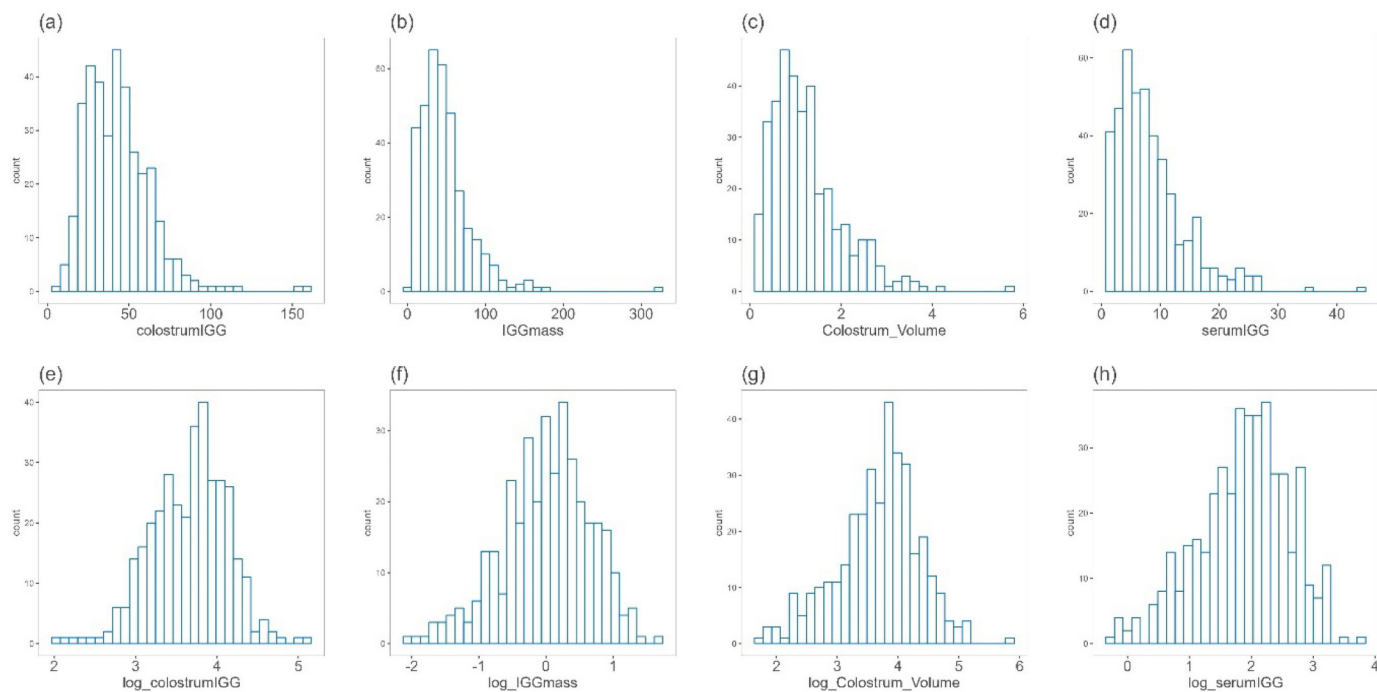


Figure 1. Distribution of colostrum [IgG], colostrum IgG_{mass}, colostrum volume and kids' serum [IgG], before (a,b,c,d) and after (e,f,g,h) normalization with a logarithmic transformation.

Table 1. Descriptive statistics of serum [IgG] in 424 female kids (1–8d old) raised in an experimental INRAE herd (P3R, Bourges, France)

Trait ¹	N	Mean (SD)	P10	P90
Serum [IgG], g/L	424	8.20 (5.87)	2.18	15.99
Log (Serum [IgG])	424	1.85 (0.75)	0.78	2.77
Day at blood sampling	424	3.73 (1.54)	2	6
Litter size (of the kid)	424	1.86 (0.68)	1	3
Weight at birth, kg	422	3.96 (0.78)	2.90	4.90
Parity of the dam	424	2.10 (1.21)	1	4
Kid's vigor at birth ²	387	2.11 (0.59)	1	3
Time to complete colostrum intake ³	386	1.25 (0.56)	1	2

¹IgG: immunoglobulin.

²scored as follows: 1 = lying down with few or no movement; 2 = standing and staggering; 3 = standing and able to move with confidence.

³scored as follows 1 = ≤ 3 h, 2 = 3–6 h, 3 = ≥ 6 h.

servations on primiparous goats). The average colostrum [IgG], IgG mass and volume of colostrum analyzed were 44.86 ± 21.41 g/L, 43.50 ± 25.15 g and 1.09 ± 0.66 L, respectively. These results were highly variable, with coefficients of variation of 47.7%, 57.8% and 60.6% for the 3 colostrum traits, respectively. Moreover, these IgG concentration values were dissymmetrically distributed (Figure 1), with a small number of potentially very high values. Therefore, logarithmic transformation was used to normalize data distribution (Figure 1).

For the 177 animals that were measured for both serum [IgG] as a kid and colostrum [IgG] as a dam at first lactation (so around 1 year of age), we observed no significant correlation between these 2 traits ($r = -0.06$, $P = 0.41$).

Table 2. Descriptive statistics of colostrum traits (volume, IgG concentration and IgG mass, fat content) from first and second milking in 101 adult goats recorded in an experimental INRAE herd (P3R, Bourges, France) in 2018 and 2019

Trait ¹	First milking			Second milking		
	Mean (SD)	P10	P90	Mean (SD)	P10	P90
Colostrum volume, L	1.08 (0.67)	0.29	1.96	0.71 (0.41)	0.22	1.30
Colostrum [IgG], g/L	45.8 (24.2)	22.3	67.5.1	26.7 (19.4)	6.16	52.9
Colostrum IgG mass, g	43.3 (26.2)	13.4	73.8	17.3 (18.2)	4.5	34.4
Fat content, g/L	71.2 (36.0)	28.0	115.2	85.8 (36.2)	42.0	135.6
Time after kidding, hh:mm	02:10 (01:26)	00:30	04:07	12:50 (05:23)	06:45	20:30

¹IgG: immunoglobulin; IgG mass: total amount of immunoglobulin in the colostrum (volume of colostrum x immunoglobulin concentration in colostrum), [IgG]: immunoglobulin concentration, SD = standard deviation, P10: percentile 10, P90: percentile 90.

Table 3. Descriptive statistics of colostrum traits (volume, IgG concentration and IgG mass) in 203 primiparous goats recorded in an experimental INRAE herd (P3R, Bourges, France) from 2018 to 2021. Milk yield was analyzed for 390 primiparous goats from the same herd and study years

Trait ¹	n	Mean (SD)	P10	P90
Colostrum volume, L	203	1.09 (0.66)	0.38	1.96
Colostrum [IgG], g/L	203	44.86 (21.41)	21.98	67.42
Colostrum IgG _{mass} , g	203	43.50 (25.15)	15.24	73.40
Log (Colostrum volume)	203	-0.01 (0.64)	-0.96	0.67
Log (Colostrum IgG _{mass})	203	3.69 (0.63)	2.72	4.30
Log (Colostrum [IgG])	203	3.70 (0.46)	3.09	4.21
MY250, kg	390	615 (121)	241	1040

¹IgG: immunoglobulin; MY250 = average milk production over 250 d (Fleishman method).

Factors associated with serum IgG concentration in kids and colostrum traits

Year of birth was significantly associated with serum IgG concentration ($P = 1.50 \times 10^{-6}$), with a maximum estimated difference between 2017 and 2021 and increased estimated mean values \pm SE in the most recent years, e.g., 1.53 ± 0.08 g/L, 1.88 ± 0.108 g/L, 1.79 ± 0.08 g/L, 1.90 ± 0.07 g/L and 2.30 ± 0.10 g/L from 2017 to 2021. We found less significant effects of the age at blood sampling ($P = 0.05$) and parity of the dam ($P = 0.06$). Serum IgG concentration decreased with increasing age at blood sampling (regression coefficient -0.05), and this correlation was linear over the range of our data. With regard to dam parity, serum IgG concentration decreased especially for kids from older mothers, with estimated means equal to 1.93 ± 0.05 , 1.94 ± 0.06 and 1.77 ± 0.06 for dam parity equal to 1, 2 or ≥ 3 respectively. There was no effect of birth weight, litter size, kid's vigor at birth and time to complete colostrum intake.

Results from linear models fitted to colostrum traits, are shown in Table 4. We found an effect of time period between parturition and colostrum sampling for colostrum IgG mass ($P = 0.07$; regression coefficient = 0.09) and colostrum volume ($P = 0.04$; regression coefficient

= of 0.10). The results showed that colostrum volume and IgG mass increased in a similar way with the time elapsed between kidding and collection (up to 6 h). Colostrum concentration was therefore unaffected. For colostrum IgG mass, we found an effect of litter size. Compared with goats with one kid, those with 2 kids or more had higher IgG mass ($P = 0.04$). The estimated mean values \pm SE were 3.52 ± 0.06 and 3.70 ± 0.07 for litters of one kid or more than one kid, respectively. Effect of year of measurement was limited, reaching significance ($P = 0.10$) only for IgG concentration.

The lack of correlation between serum [IgG] as a kid and colostrum [IgG] as a dam, suggest that factors linked to the mother's condition a few weeks before parturition (body condition before parturition, litter size, ...) probably had an impact on the quality of their colostrum, which was far more important than IgG ingestion when the animal was a newborn.

Association between serum IgG and health disorders in kids

Measurements of early-life health indicators included 1816 observations on 395 (out of 424) kids for each indicator. The most frequently reported disorder (Table 5) was abnormal temperature with 47.9% of kids affected at least once during the observation period. This health disorder is followed by nasal discharge, with at least one occurrence on 25.3% of the kids, eye discharge (19.7%) and 15.9% of kids suffering from diarrhea. We found significant phenotypic correlations of 0.48 ($P < 2.2 \times 10^{-16}$) between hindquarters cleanliness and the occurrence of diarrhea and of 0.44 ($P < 2.2 \times 10^{-16}$) between the occurrence of eye and nasal discharges. All other indicators were weakly correlated.

Serum IgG concentration was significantly associated (Table 6) with several early-life health indicators, including soiled hindquarters ($P = 0.003$), and both nasal discharge ($P = 0.022$) and eye discharge ($P = 0.022$) but

Table 4. Ancova results for colostrum traits (IgG concentration, IgG mass and volume) at first milking in 203 primiparous goats recorded in an experimental INRAE herd (P3R, Bourges, France)

Effect	Colostrum [IgG] ² , g/L	Colostrum IgG _{mass} ² , g	Colostrum volume ² , L
Year	$P = 0.10$	$P = 0.15$	$P = 0.44$
2018 (n = 39)	3.74 (± 0.07)	3.52 (± 0.10)	-0.22 (± 0.10)
2019 (n = 64)	3.67 (± 0.06)	3.70 (± 0.08)	-0.01 (± 0.08)
2020 (n = 50)	3.60 (± 0.06)	3.48 (± 0.09)	-0.15 (± 0.09)
2021 (n = 50)	3.82 (± 0.06)	3.71 (± 0.09)	-0.11 (± 0.09)
Litter size	$P = 0.18$	$P = 0.04$	$P = 0.50$
1 (n = 121)	3.67 (± 0.04)	3.52 (± 0.06)	-0.15 (± 0.06)
2 (n = 82)	3.76 (± 0.05)	3.70 (± 0.07)	-0.09 (± 0.07)
Time ¹	$P = 0.67$	$P = 0.07$	$P = 0.04$

¹Time = Time from kidding to first milking when colostrum sample was weighted, and sampled for analysis.

²All Colostrum traits are log-transformed.

Table 5. Descriptive statistics of health records taken on 395 goat kids in an experimental INRAE herd (P3R, Bourges, France). Observations were made weekly between the first and fifth week of age. Binary variables were summarized as a 0 (no occurrence) / 1 (at least one occurrence) over the observation period

Health condition	N (%)		
	[0–2[[2–3[≥3
Hindquarters Cleanliness ¹	173 (43.8%)	182 (46.1%)	40 (10.1%)
	Absence	Presence	
Diarrhea	332 (84.1%)	63 (15.9%)	
Nasal Discharge	295 (74.7%)	100 (25.3%)	
Eye Discharge	317 (80.3%)	78 (19.7%)	
Abnormal temperature ²	149 (52.1%)	137 (47.9%)	
Breathing Difficulties	395 (100%)	0 (0%)	

¹ $= \log \sum_{week=1}^5 obs^2$, with obs = 1 (clean), 2 (fecal matter visible when tail is lifted), 3 (fecal matter visible on the peripheral area of the tail).

²Abnormal temperature were temperatures > 39.5°C.

not diarrhea ($P = 0.779$) nor rectal temperature above 39.5°C ($P = 0.602$). The magnitude and linearity of the effect are also illustrated in Figure 2, which shows that the probability of health disorders decreases as serum IgG concentration increases. The following raw data also confirm this. Animals with no occurrence of soiled hindquarters presented an average serum [IgG] of 8.82 ± 5.94 g/L whereas animals showing at least one occurrence of soiled hindquarters had an average serum [IgG] of 6.62 ± 4.83 g/L. Average serum [IgG] was equal to 9.08 ± 6.07 g/L vs 5.27 ± 3.90 g/L for animals not presenting or presenting eye discharges respectively. Average serum [IgG] was equal to 9.13 ± 6.23 g/L vs 5.96 ± 3.95 g/L for animals not presenting or presenting nasal discharges respectively.

The total absence of breathing difficulties during the 5 years of study prevented us from analyzing any association with the quality of passive immunity transfer.

Genetic parameters

Results of variance components and heritabilities are given in Table 7. Heritability of serum [IgG] was not significantly different from zero. The permanent environment of the dam showed low variance equal to 0.052. Heritability of colostrum traits were moderate, with estimates of 0.25 ± 0.16 and 0.35 ± 0.16 , and 0.25 ± 0.16 for [IgG], IgG mass and volume, respectively.

Genetic correlations between colostrum IgG mass and both IgG concentration (0.74 ± 0.36) and colostrum volume (0.84 ± 0.20) were high (Table 8). However, colostrum [IgG] was genetically independent from colostrum volume. Genetic correlations with milk production was significantly different from zero between MY250 and colostrum IgG concentration ($rg = -0.44 \pm 0.33$), close to significance for colostrum volume ($rg = 0.35 \pm 0.37$) but not significant with IgG mass ($rg = 0.01 \pm 0.35$). The higher the milk production, the greater the volume of colostrum, but the lower the IgG concentration.

DISCUSSION

In the present study, the concentration of immunoglobulin in Alpine goat colostrum (44.86 ± 21.41 g/L), was similar to previously published data for other dairy goat breeds, ranging from 26.6 ± 12.6 to 47.7 ± 12.6 g/L (Kessler et al., 2019), and up to 54.4 ± 26.4 g/L (Rudovsky et al., 2008) or 63.4 ± 35.4 g/L (Zobel et al., 2020). The IgG concentration of colostrum, has also been documented in other ruminants, e.g., in meat goats, meat and dairy sheep (Gilbert et al., 1988; Kessler et al., 2019), and meat and dairy cattle (Derbakova et al., 2020; Martin et al., 2021). Similar values were reported in these studies, and even higher values such as 61.0 ± 10.3 g/L in Boer goat (Kessler et al., 2019) or 70.7 ± 26.6 g/L in dairy cattle (Derbakova et al., 2020). Variation among studies is in part explained by differ-

Table 6. Factors affecting health condition of 395 goat kids in an experimental INRAE herd (P3R, Bourges, France). Health records were made weekly between the first and fifth week of age. Binary variables were summarized as a 0 (no occurrence) / 1 (at least one occurrence) over the observation period

Health condition	Factors of variation (P value)				
	Log (serum [IgG]) ³	Year of birth ⁴	Birth weight ³	Litter size ⁴	Vigor at birth ⁴
Hindquarters Cleanliness ¹	0.003	1.21×10^{-9}	0.033	0.983	0.921
Diarrhea	0.779	0.001	0.314	0.559	0.687
Nasal Discharge	0.022	2.0×10^{-16}	0.799	0.072	0.014
Eye Discharge	0.022	2.0×10^{-16}	0.123	0.420	0.969
Abnormal temperature ²	0.602	0.018	0.868	0.660	0.757

¹ $= \log \sum_{week=1}^5 obs^2$, with obs = 1 (clean), 2 (fecal matter visible when tail is lifted), 3 (fecal matter visible on the peripheral area of the tail).

²Abnormal temperature were temperatures > 39.5°C.

³as covariable in the model.

⁴as class variable in the model.

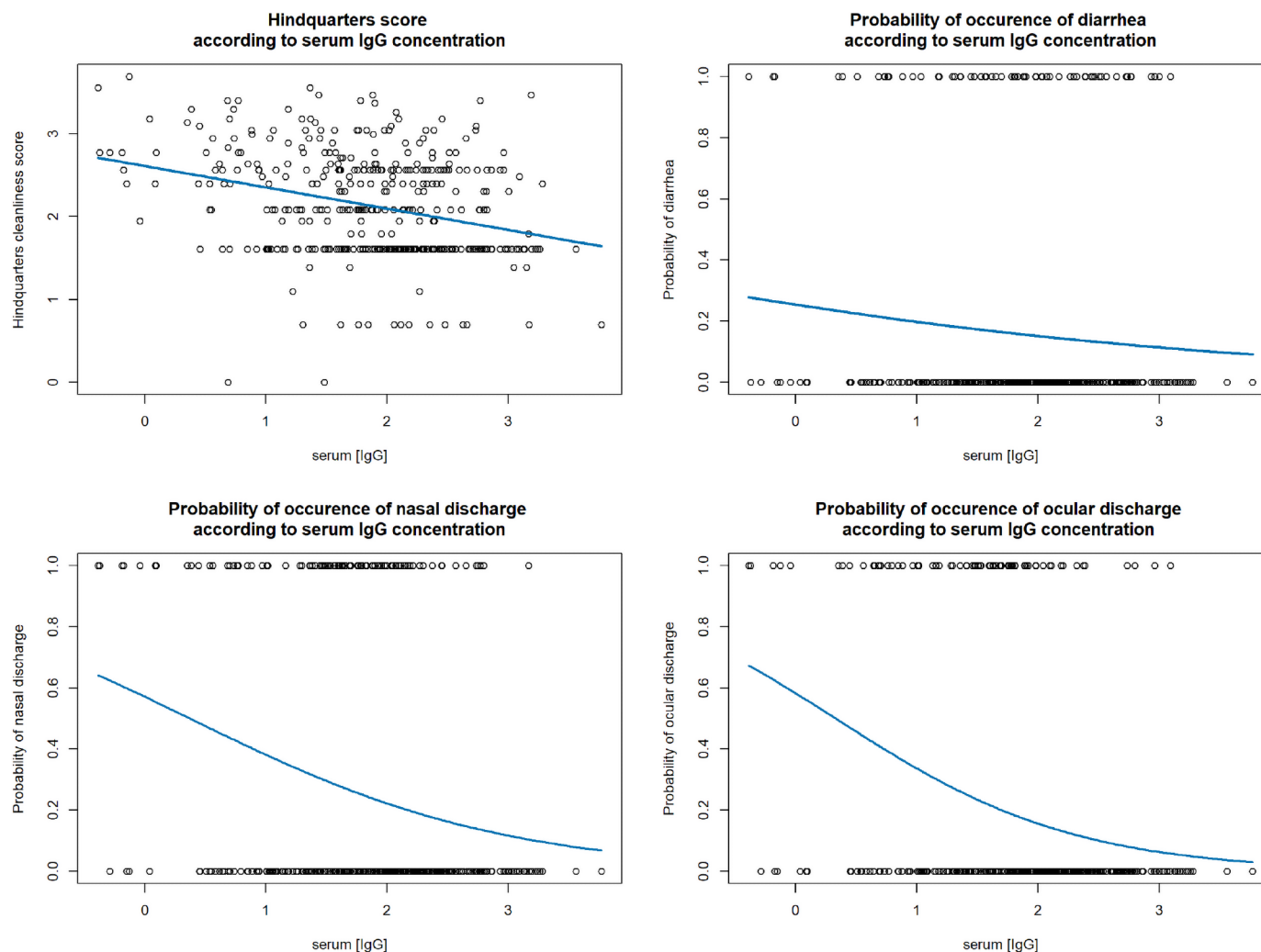


Figure 2. Changes in the probability of developing health problems, such as (a) soiled hindquarters, (b) diarrhea, (c) ocular discharge, (d) nasal discharge in the first 5 weeks of life as a function of log(serum [IgG]) in kids

ence in methodology for estimating IgG concentration, the gold standard RID yielding higher results than others techniques such as ELISA or Brix refractometer (Zobel et al., 2020). However, more than technique and species, the difference in colostrum IgG concentration seems to be associated with breed type. Meat breeds are associated

to higher IgG concentrations than dairy breeds (Kessler et al., 2019; McGee and Earley, 2019), which is probably linked to the volume produced. Altogether, these studies confirm the high inter individual variability associated with this trait.

Table 7. Variance components and heritabilities (h^2) of serum [IgG] in female kids and colostrum traits (volume, IgG concentration and IgG mass) in adult goats recorded in an experimental INRAE herd (P3R, Bourges, France)

Trait ^{1,2}	N	σ^2_a	σ^2_c	$\sigma^2_{p\text{mother}}$	$h^2 \pm SE$
Serum [IgG], g/L	424	0.020	0.398	0.052	0.04 ± 0.07
Colostrum [IgG], g/L	203	0.054	0.159		0.25 ± 0.16
Colostrum IgG mass, g	203	0.134	0.245		0.35 ± 0.16
Colostrum volume, L	203	0.102	0.309		0.25 ± 0.16
MY250, kg	390	3565	8815		0.29 ± 0.12

¹IgG: immunoglobulin; MY250 = average milk production over 250 d (Fleishman method).

²All IgG traits (serum and colostrum) and Colostrum volume are log-transformed.

Environmental and physiological factors, such as year, litter size and sampling time, affected colostrum traits. We can hypothesize that the effect of the year is linked to changes in management (food, person in charge of sampling) or to changes in environmental conditions (temperature, humidity), but in all cases the effect of the year is moderate. Interestingly IgG concentration was not affected by litter size, as found by Kessler et al. (2019), as IgG volume and quantity also increased with litter size. The apparent correspondence between antibody production by the mother and the number of kids for which passive immune transfer is required is not, however, offset by the total amount of IgG produced; indeed, for litters of 2 kids (46.4 ± 1.0 g, i.e., 23.2 g per kid) this amount is not doubled compared with litters with singletons (33.5 ± 1.0 g).

The low serum IgG concentration we found (8.20 ± 5.87 g/L) is similar to that reported by other authors in France, Ehrhardt et al. (2014). Similarly, Mellado et al. (2008) found a mean concentration of 10.1 ± 11.4 g/L at 24 h of age, for kid fed with artificial colostrum. Several hypotheses may explain why some kids had particularly low IgG concentrations in our study. First, the kids received a fixed dose of 300 mL of colostrum, whereas the recommended dose is 10% of the kids' live weight. Birth weight was on average 3.96 ± 0.78 kg with a maximum value of 5.9 kg. As a result, some kids weighing over 3 kg at birth may not have had enough colostrum. This hypothesis was not supported here, as there was no effect of birth weight on serum IgG concentration. On the other hand, we unfortunately do not know the quality of the colostrum mixes distributed, so it is likely that this had an influence on serum IgG concentration. Furthermore, this variability in serum IgG concentration may also be explained by the kid's intrinsic ability to absorb and metabolize ingested IgG (Maltecca et al., 2007).

In the present study we found a significant effect of serum IgG level on the health status of kids up to 2 mo of age. As expected, the absorption of IgG in the days following birth is essential to ensure the passive transfer of immunity from the mother to the youngster, and provide immune protection against various disorders of

the digestive and respiratory tracts. This result agrees with the study of Basoglu and Camkerten (1999) who compared a group of calves with diarrhea and a group of healthy calves. Among the latter, none of them had a TPI failure (IgG levels lower than 8 g/L) compared with 35% for the group of diarrheic calves. In addition, Ithurbide et al. (2022) studied the survival of goats from the same herd as in the present study. They showed that the survival through life was significantly better when serum IgG concentration shortly after birth was higher. They have thus demonstrated that the deleterious effect of a deficient immune transfer persists even during the later stages of life. However, we should highlight that, in our study, health data on the kids were recorded once a week for practical reasons. We can wonder whether some kids could have developed health problems and recovered in less than a week. Therefore, a higher frequency of measurement would have enabled us to detect the presence of health issues more accurately.

Heritability of serum [IgG] was not significantly different from zero. This low value, with large SE, may be due to the limited data size and to many factors influencing this trait that we have not considered and analyzed in our study, thus increasing the residual variability. Essentially, we can stress that our study does not consider the quality of the colostrum distributed, and thus, the amount of IgG ingested by the kid, which is likely to be highly variable and have a significant effect on heritability estimates. In fact, the colostrum distributed on this farm is made up of a mixture of colostrum from several goats, and is administered after being thermized to prevent transmission of the Caprine Arthritis Encephalitis virus. Unfortunately, we did not have access to the composition of these colostrum pools or their IgG concentration. This was different from cattle literature, which reports significant heritability for Ig concentration in calves' serum varying from 0.18 (Maltecca et al., 2009), from 0.20 to 0.36 (Martin et al., 2021) and from 0.25 to 0.59 (Cordero-Solorzano et al., 2022). In addition, Haagen et al. (2021) found a moderate heritability of 0.06 ± 0.01 for total serum protein content. In sheep, Gilbert et al. (1988) also found a significant moderate heritability of

Table 8. Genetic (above the diagonal) and phenotypic (below the diagonal) correlations among colostrum traits (volume, IgG concentration and IgG mass) and milk production in adult goats recorded in an experimental INRAE herd (P3R, Bourges, France)

Trait ^{1,2}	Colostrum [IgG]	Colostrum IgG _{mass}	Colostrum volume	MY250
Colostrum [IgG]		0.74 ± 0.36	0.26 ± 0.78	-0.44 ± 0.33
Colostrum IgG _{mass}	0.33 ± 0.06		0.84 ± 0.20	0.01 ± 0.35
Colostrum volume	-0.39 ± 0.06	0.74 ± 0.03		0.35 ± 0.37
MY250	-0.09 ± 0.07	0.18 ± 0.07	0.24 ± 0.07	

¹IgG: immunoglobulin; MY250 = average milk production over 250 d (Fleishman method).

²All colostrum traits are log-transformed.

0.18 ± 0.06 , perhaps due to the large number of lambs ($n = 964$) and the mode of colostrum intake (maternal suckling).

Significant heritabilities were found for colostrum traits, ranging from 0.25 ± 0.16 to 0.35 ± 0.16 , suggesting genetic control of colostrum components in goats. To our knowledge, these are the first estimates of heritability for such traits in goats. The heritability of IgG concentration in colostrum (0.24 ± 0.17) was similar to the heritability of IgG assayed by Brix estimated in sheep by Gilbert et al. (1988) which was equal to 0.19 ± 0.12 . Results were also close to cattle estimates for IgG assayed by Brix or RID, equal to 0.20 ± 0.09 (Cordero-Solorzano et al., 2022), 0.27 ± 0.09 (Soufleri et al., 2019) and 0.28 ± 0.14 (Martin et al., 2021). In cattle, lower heritabilities were also reported when ELISA was used to estimate IgG concentration, with estimates between 0.08 ± 0.12 (Martin et al., 2021) and 0.10 ± 0.08 (Conneely et al., 2013). This suggests that RID, and possibly Brix, provide sufficiently robust IgG concentration estimates when genetic analysis or application is intended. In our study, we also estimated genetic parameters for colostrum volume and total IgG mass to disentangle the genetic determinism of the underlying components of IgG concentration. IgG mass showed a higher heritability (0.35 ± 0.16), but as the measure requires the measurement of colostrum volume, its operationality for selection seems weaker. Given that the genetic correlation of IgG concentration with both IgG mass and colostrum volume is high (0.74 – 0.84), selection on IgG concentration should result in a beneficial correlated response for IgG total quantity.

Genetic correlations with milk production showed high standard errors due to small numbers. However, they suggest a negative genetic association between milk production and IgG concentration in colostrum, probably linked to a positive dilution association with total colostrum volume. Indeed, the total IgG quantity in colostrum seemed to be genetically independent from milk production. The latter results suggest that there is no major deterioration in colostrum quality in response to selection for increased milk production, but that there is room to genetically improve colostrum quality. These findings should be confirmed on larger data sets.

CONCLUSION

The study investigated for the first time genetic and environmental factors associated with immunoglobulin G in the kid serum and doe colostrum in Alpine dairy goats. As expected, IgG absorption in the days following birth has been shown to be essential for the passive transfer of immunity from mother to kid, and to provide immune protection against various digestive and respiratory tract disorders. Significant heritabilities were found

for colostrum traits, ranging from 0.25 ± 0.16 to 0.35 ± 0.16 , suggesting genetic control of colostrum components in goats. The main limitation of the study was the sample size used for the genetic analyses. Collectively these results open up opportunities for genetic improvement of colostrum quality in goats.

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Supplemental Material: **Datasets used in the present study are available on the following zenodo platform link. Rupp, R. (2024). Datasets on Immunoglobulin G in kid serum and adult colostrum of dairy goats [Data set]. Zenodo.** <https://doi.org/10.5281/zenodo.13222012>

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ORCID

- M. Wicki  <https://orcid.org/0000-0002-3585-1572>
 F. Corbière  <https://orcid.org/0000-0003-3006-5561>
 R. Rupp  <https://orcid.org/0000-0003-3375-5816>