Can nonlinear heart rate variability analysis be used to characterize the sow social hierarchy within group-housed gestation systems?

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Abstract

Establishment of social hierarchy within gestation group housing may lead to increased stress for low-ranked sows. The study objective was to evaluate use of nonlinear heart rate (HR) variability as a potential future tool for characterizing social hierarchies. Five groups of sows (≥ 12 sows in each group) were enrolled. One day prior to weaning, baseline HR data were collected from 10 sows in each group for 60 min while in individual farrowing crates. The following day, HR data were collected from the same 10 sows for 240 min after returning to group-housing (reintroduction). Stored HR data were used to calculate sample entropy (SampEn) and short-term detrended fluctuation analysis ($DFA_{\alpha1}$). Aggressive interactions during reintroduction were used to determine social rank. Sows were classified into one of four rank quartiles (RQ), where RQ1 were high-ranking sows. For baseline, RQ affected SampEn and $DFA_{\alpha1}$ ($P < 0.001$ for both), with RQ1 exhibiting greater SampEn ($P < 0.01$) and a lower $DFA_{\alpha1}$ value ($P < 0.001$) compared to all other RQ. Additionally, RQ4 had greater SampEn and $DFA_{\alpha1}$ than RQ3 ($P = 0.02$ and 0.03, respectively). No other baseline differences were observed between RQ ($P > 0.1$). After reintroduction, RQ4 tended to have lower SampEn than RQ3 ($P = 0.08$), with no other differences between RQ for SampEn or $DFA_{\alpha1}$ ($P > 0.1$). Based on these data, baseline SampEn and $DFA_{\alpha1}$ has potential to predict high-ranking sows in group-housing. Future work needs to investigate other HR measurements as potential predictors of lower-ranked sows.

Keywords: heart rate variability, nonlinear variability analysis, social hierarchy, swine, welfare

Introduction

Approximately 33% of sow farms in the United States utilize group gestation housing, where sows are housed in pens along with their conspecifics during the gestation phase (personal communication with the National Pork Producer's Council, 2022). Traditional sow housing during the gestation phase utilizes individual gestation stalls, which allow producers to closely monitor gestation progress and sow health. However, stall-housed sows are largely inhibited from performing their normal range of behaviors, including turning around and social interaction (Barnett et al., 2001). The inability to perform these behaviors has led to consumer, corporate, and governmental demand for increased sow space during the gestation phase (Tonsor et al., 2009). As a result, many producers have transitioned from traditional stall housing to group gestation systems.

While group gestation does give individual sows the ability to express more natural behaviors compared to traditional stall housing, sow welfare challenges remain. One major example of this involves the determination and maintenance of the social hierarchy within the pen. Social hierarchies established by individual animals within pen housing arise due to competition for access to resources, like feed (Maes et al., 2016). The process typically involves aggressive interactions between individual sows during the initial hours after mixing (Arey and Edwards, 1998), which can lead to injury. Additionally, after the hierarchy is largely established, access to resources may be inhibited for certain individuals throughout the gestation period, which could further reduce that individual's welfare (Arey and Edwards, 1998).

Quantification of the social hierarchy within sow group gestation housing is time consuming and detection is not feasible for a producer. However, if knowledge of the social hierarchy within the pen could be detected automatically using precision technologies, a producer may be able to identify and monitor sows at higher risk of poor welfare outcomes due to their position within the hierarchy. As a result, strategies aimed at reducing hierarchy-based aggressive interactions and increasing access to needed resources could be employed for specific sows to improve their longevity within the reproductive herd.

Heart rate variability (HRV), or the variation in length between adjacent heart beats over a period of time, may be a promising future technology for automated detection of stress related to hierarchy. Heart rate variability is commonly used to measure stress in studies on animal welfare (von Borell et al., 2007). It improves upon simple heart rate (HR) measurement by evaluating the variability that is present in instantaneous heart rate data over time, which can be used as a proxy measure of autonomic nervous system function in response to a stressor (von Borell et al., 2007). However, measurement of HRV also has drawbacks. For example, HRV is currently too time-intensive for on-farm production application. Additionally, the most commonly used methods for measuring HRV utilize traditional linear measures of amount (i.e. mean) and magnitude (*i.e.* standard deviation) instead of variability measures that are capable of detecting HR dynamics that are commonly "*non-stationary, intermittent, scale-invariant, and nonlinear* (Valenza et al., 2017)." As a result, changes to variability that result from exposure to a stressor may go undetected (Byrd et al., 2019).

To address these issues, recent studies have indicated that real-time detection of instantaneous HR collection is possible using automated camera systems (Wang et al., 2021) and sensors worn by animals in production (Nie et al., 2020). Additionally, the use of nonlinear variability measures rooted in chaos and complexity theories have been utilized in animal welfare studies for detecting complex, but predictable, temporal HRV structure and organization that is not observable with linear measurement. Two examples include sample entropy (SampEn; Table 1), which attempts to measure the regularity of a time series (Delgado-Bonal and Marshak, 2019), and short-term detrended fluctuation analysis ($DFA_{\alpha1}$; Table 1), a measure of fractal-like complexity, or the statistical self-similarity of a time series at different timescales (Goldberger et al., 2002). Both have been found to be useful for detecting physiological stress, where reduced stress leads to decreased HRV regularity (*i.e.* greater SampEn; Byrd et al., 2019) and a $DFA_{\alpha1}$ value near 1.0 (on a scale of 0.5 – 1.5), which indicates the presence of increased fractal-like complexity (*i.e.* self-similarity) of the HRV data (Goldberger et al., 2002).

Given the potential promise of HRV and nonlinear variability analyses for measuring animal stress, the purpose of this study was to determine whether nonlinear analyses of heart rate variability could be utilized to characterize the sow social hierarchy within group gestation housing. We hypothesized that high-ranking sows would exhibit evidence of reduced physiological stress compared to low-ranking sows following introduction to group gestation housing. Specifically, we predicted that high-ranking sows would exhibit greater SampEn than lower-ranking sows after moving to group gestation. Additionally, high-ranking sows would exhibit a $DFA_{\alpha1}$ value near 1.0 compared to lower-ranking sows, who would exhibit a $DFA_{\alpha1}$ value closer to 1.5.

Materials and methods

All experimental procedures were carried out at the North Dakota State University Swine Research and Teaching Unit in Fargo, ND USA (Approved IACUC # A21044).

Animals and housing

Fifty gestating sows (10 per replicate over 5 repetitions) were randomly selected to undergo heart rate variability data collection during the experimental procedure. All sows were initially housed in individual farrowing stalls (1.83 x 0.74 m) on slatted cast iron flooring immediately prior to farrowing and during the nursing period. Each farrowing stall included two drinkers that provided *ad libitum* access to water and a feeder bowl. Each sow received 1.36 kg of a lactation diet formulated to contain 11% as-fed crude protein twice daily until farrowing. After farrowing, sows were fed to appetite with rations increasing by 0.91 kg each day until the total ration equaled a maximum of 7.26 kg per d. Room temperature was environmentally controlled to maintain sow thermal comfort. Individual heat lamps within each stall provided supplemental heat for the piglets. Artificial light was provided from approximately 0730 h until 1500 h. Some natural lighting during daylight hours was provided through the ventilation fans on the south side of the building.

Following weaning, all sows were moved to one of four group-gestation pens (7.30 x 7.62 m) within the facility. Each group gestation pen consists of two resting areas (2.30 x 2.24 m) separated by a "T" shaped protecting wall and a larger communal area equipped with two electronic sow feeders (Big Dutchman, Holland, MI USA) and three water cups with nipples. The concrete floor within each pen is partially slatted. Room temperature within the facility was environmentally controlled and artificial lighting was provided between approximately 0730 h and 1500 h. Each sow received up to 1.81 kg of gestation feed formulated to contain 18% as-fed crude protein daily throughout the gestation phase.

Heart rate variability data collection and analysis

Seven days prior to weaning and relocation to group-gestation housing, all sows in farrowing stalls began acclimation to the HR monitors (Polar H10 Heart Rate Sensor, Polar Electro, Kempele, Finland) used to collect HRV data. A HR monitor connected to an electrode strap with electrode gel (Spectra 360 Electrode Gel, Parker Laboratories Inc., Fairfield, NJ USA) applied was fitted immediately behind the sow's front legs, with the monitor and electrode strap positioned over the location of the sow's heart. After 30 min, the monitor and electrode strap were removed. This procedure was repeated two additional times for each sow over the next 5 d.

All sows selected for HRV collection underwent 60 min of data collection 1 d prior to weaning while they were housed in individual farrowing stalls. The HR monitor and strap were placed as previously described. After confirming HR detection, flexible veterinary bandage (VetWrap; 3M, Maplewood, MN USA) was placed over the HR monitor and strap to keep them in place. The data were collected, transmitted via Bluetooth technology, and stored using a freely available HRV application (Elite HRV, Asheville, NC USA) downloaded to an iPod (Apple Inc., Cupertino, CA USA). After 60 min, the HR monitors were removed.

The following day, all sows underwent a second HRV data collection. Heart rate monitors were fitted prior to weaning but data collection did not begin until immediately after the sows were mixed in gestation housing. After 140 min of HRV data collection, all HR monitors and electrode straps were removed.

All instantaneous HR data were downloaded from the EliteHRV application following the data collection period, displayed in a computer spreadsheet software (Microsoft Excel; Microsoft Corp., Redmond, WA USA), and manually evaluated for errors. Two 5-min datasets with fewer than 5% erroneous inter-beat intervals were selected for each sow (one from the baseline period, one from the group-housing reintroduction period). Any errors observed within the two selected datasets per sow were edited using previously published editing guidelines (Marchant-Forde et al., 2004). All data utilized for analysis occurred during periods of rest, where the sow was lying laterally or sternally.

Sample entropy (Table 1) and $DFA_{\alpha1}$ (Table 1) were determined using a freely available software program designed for HRV analysis (Kubios HRV Standard, Kubios Oy, Kuopio, Finland). An embedding dimension of 2 beats and a tolerance of 0.15 x SD were utilized for calculation of SampEn. For $DFA_{\alpha1}$, a short-term fluctuation was defined as 4-16 beats.

Table 1: Definitions of nonlinear heart rate variability measures utilized in the study.

Trait	Definition
Sample Entropy (SampEn), bits	The negative value of the logarithm of the conditional probability that two similar sequences of *m* points remain similar at the next point *m*+1, counting each vector over all other vectors except on itself (Delgado-Bonal and Marshak, 2019). Sample entropy is measure of time series regularity where a lower value indicates greater regularity. In many studies focused on animal stress, regularity (as measured by SampEn) is greater when physiological stress increases (Byrd et al., 2019).
Short-Term Detrended Fluctuation Analysis ($DFA_{\alpha1}$), α	Quantifies fractal-like correlation properties within a data set by calculating the scaling property of the root-mean-square fluctuation of the integrated and detrended time series data (Yeh et al., 2006). An exponent $\alpha = 1$ represents long-range fractal-like correlations (*i.e.* self-similarity) between data at different timescales, while an exponent α near 0.5 represents random time series data (Gaussian noise) and an exponent α near 1.5 represents short-term correlation (Brownian noise). Previous studies indicate that an exponent $\alpha = 1$ is commonly observed in cases of healthy heart rate regulation and reduced physiological stress (Goldberger et al., 2002).

Sow social hierarchy determination

Sow behavior was utilized to determine the social hierarchy within the group gestation pen. Immediately after entering the group gestation pen, all sow behavior was recorded using four CCTV video cameras (Lorex LBV2531U Security Cameras, Lorex Technology Inc., Markham, Canada) that had been strategically mounted above the pen to ensure a complete view of the entire area. The recorded video was transmitted to a coaxial digital video recorder (Lorex D441A6B-Z DVR, Lorex Technology Inc., Markham, Canada) located within the same room of the facility. Behavioral recording lasted for 96 h but only the initial 12 h of video were utilized for analysis, since very few changes to the hierarchy occurred during a preliminary study where the social hierarchy was compared at 12, 24, and 36 h.

A previously published methodology for determining the sow social hierarchy based on agonistic interactions between dyads was utilized in the current study (Stukenborg et al., 2011). An agonistic interaction was defined as a fight or displacement with physical contact initiated by one individual that included aggressive behavior followed by any submissive behavior performed by either individual involved in the encounter. Parallel pressing, inverse parallel pressing, head-to-head knock, head-to-body knock, levering, biting, and physical displacement were considered aggressive behaviors. Retreating during a fight, turning away from an attack, attempting to flee, or displacement from a location were considered submissive behaviors (Jensen, 1980).

Recorded video was viewed continuously for 12 h. All interactions that included aggressive and submissive behaviors between dyads of sows were recorded by a single observer using a behavioral coding software (The Observer XT 15; Noldus Information Technology, Wageningen, Netherlands). During the agonistic interaction, a sow that performed one of the submissive behaviors was considered to be "defeated," while the other sow was deemed the "winner." These data were used to calculate a dominance index (1) based on aggressive interaction "wins" and "defeats" for each individual sow, where a DI closest to 1.00 indicated the highest-ranking sows and a DI closest to -1.00 indicated the lowest-ranking sows.

$$DI = \frac{(\text{ì1miRäoîo1pi})}{(\text{ì1mi5äoîo1pi})} \quad (1)$$

Sows were then categorized into one of four rank quartiles (RQ) based on their DI. The HRV results presented here represent one component of a larger swine social hierarchy study, which consisted of 5 gestation groups with unequal sample sizes (range n = 12-17 sows per repetition). Since it was not possible to ensure equal group sizes, rank quartiles were used to standardize between gestation groups. Sows in RQ1 were ranked highest and sows in RQ4 were ranked lowest. Rank quartile 2 and RQ3 sows were intermediate to RQ1 and RQ4 sows.

Statistical analysis

Data were analyzed in SAS (v. 9.4; SAS Institute, Inc., Cary, NC). Heart rate variability data were analyzed using the MIXED procedure. For both baseline and post-mixing HRV measurement, RQ was included as a fixed effect, age as a covariate, and sow and repetition as random effects. Each sow's baseline HRV measurement was also used as a covariate in the post-mixing HRV models. A *P*-value less than 0.05 was considered significant for all models.

Results and discussion

All results are presented in Table 2. During the baseline period, RQ affected SampEn and $DFA_{\alpha1}$ ($P < 0.001$ for both), with RQ1 exhibiting greater SampEn ($P < 0.01$) and a lower DFAα1 value ($P < 0.001$) compared to all other RQ. Additionally, RQ4 had greater SampEn and $DFA_{\alpha1}$ than RQ3 ($P = 0.02$ and 0.03, respectively). No other baseline differences were observed between RQ ($P > 0.1$). After reintroduction, RQ4 tended to have lower SampEn than RQ3 ($P = 0.08$), with no other differences between RQ for SampEn or $DFA_{\alpha1}$ ($P > 0.1$).

Table 2: Effect of rank quartile (RQ[1]) on nonlinear heart rate variability before (Baseline) and after (Post-mixing) introduction to group gestation housing.

	Trait[3]	RQ1	RQ2	RQ3	RQ4	*P*-value
Baseline[2]	*SampEn*	1.79 ± 0.13[a]	1.15 ± 0.12[bc]	1.15 ± 0.10[c]	1.34 ± 0.12[b]	<0.0001
	$DFA_{\alpha1}$	1.00 ± 0.08[c]	1.29 ± 0.08[ab]	1.34 ± 0.07[b]	1.44 ± 0.08[a]	0.001
Post-Mixing[2]	*SampEn*	1.03 ± 0.23	1.28 ± 0.23	1.50 ± 0.17	1.08 ± 0.23	0.20
	$DFA_{\alpha1}$	1.35 ± 0.18	1.39 ± 0.17	1.14 ± 0.13	1.35 ± 0.18	0.36

[1]Rank Quartile. Rank Quartile 1 sows were ranked highest in the social hierarchy. Rank Quartile 4 sows were ranked lowest. Rank Quartile 2 and RQ3 sows were intermediately ranked.

[2]Baseline = Experimental data collection occurred approximately 24 h prior to weaning; Post Mixing = Experimental data collection occurred immediately after weaning when sows returned to group-gestation housing.

[3]SampEn = Sample Entropy; $DFA_{\alpha1}$ = Short-term detrended fluctuation analysis

To our knowledge, this is the first study that has attempted to utilize HRV as a tool for characterizing the sow social hierarchy within a group gestation system. Until recently, the use of HR or HRV for detection of stress by on-farm precision technologies was not possible. However, with the introduction of camera-based automated surveillance and sensors in production settings (Nie et al., 2020; Wang et al., 2021), the use of HRV in a production setting is becoming more likely and could be useful for automatically identifying animals at risk of poor welfare outcomes.

We predicted that high-ranking group housed sows would exhibit a greater SampEn value and a $DFA_{\alpha 1}$ value closer to 1.0 compared to lower ranking sows during the initial 4 h after all sows were reintroduced to group gestation housing. However, there were no differences between RQs for either SampEn or $DFA_{\alpha 1}$. Accordingly, HRV may not be useful for characterizing the social hierarchy when sows are housed in groups.

Surprisingly, both SampEn and $DFA_{\alpha 1}$ were capable of differentiating RQ1 sows from all other RQs when their HRV data were collected while they were still housed in an individual farrowing stall prior to moving to group gestation. Additionally, their SampEn and $DFA_{\alpha 1}$ values were consistent with livestock species that experience reduced physiological stress (Byrd et al., 2019; 2022) and humans that are experiencing reduced psychological stress (Dimitriev et al., 2016).

One potential explanation for this result may have to do with individual pig coping styles (Janczak et al., 2003), where some pigs consistently display bolder, or more “proactive”, behaviors towards conspecifics, including aggression (Koolhaas et al., 2010). Others are less bold and are considered to possess a “reactive” coping style (Koolhaas et al., 2010). It is possible that the HRV results observed in the current study represent an aspect of individual sow coping style, even before introduction to group housing. Previous studies have shown that higher-ranking sows behave “boldly” by performing more aggressive head knocks and are more likely to instigate aggressive interactions in group housing (Greenwood et al., 2017). However, pigs possessing proactive coping styles also display increased plasma concentrations of noradrenaline at baseline and in response to stress (Kanitz et al., 2019), potentially indicating increased sympathetic activity before and during stressful encounters. Therefore, if baseline HRV is capable of detecting distinct coping styles between high- and low-ranking sows, one might expect highly-ranked sows to exhibit an HRV response indicative of increased stress instead of decreased stress similar to the RQ1 responses observed here. Since the current study did not evaluate coping style, further investigation is needed to determine whether the observed relationship between HRV and social hierarchy is at least partially due to individual sow coping style.

Conclusions

The current study attempted to determine whether nonlinear HRV measures could be useful for characterizing the sow social hierarchy in group gestation housing. Our results indicate that SampEn and $DFA_{\alpha 1}$ from data collected before mixing in group housing are capable of distinguishing high-ranking sows (RQ1) from the remaining sows in the group. However, no differences in the same HRV measures were observed once all sows were mixed in the group gestation pen. Given recent technological improvements that will likely lead to automated HR collection on-farm, HRV information could be used to identify sows that will be highly-ranked once they are moved into group gestation housing. As a result, producers will be able to observe them more closely and mitigate any potential issues within the pen that could lead to poor welfare outcomes for lower-ranking sows.

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