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Fundamental frequency of neonatal crying: Does body size matter?

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Abstract

Summary: The objective of this study was to determine the influence of fetal growth on the fundamental frequency (F_0) of neonatal crying in a group of healthy full term infants. The spontaneous cries of 131 infants were audio recorded during the first week of life, and subsequently submitted to acoustic analyses. The individual cry utterances produced by each infant were measured for minimum, mean, and maximum F_0. The infants were placed into one of three groupings (low, average, high) based on body size indices according to the ponderal index (PI), the ratio of body weight to body length (BW/L), and body weight (BW) alone. The F_0 features of infants in each sub-grouping of body size were compared and contrasted. The results indicated that features of cry F_0 were found to decrease marginally as a function of increased body size, with significant group differences confined to maximum F_0. The BW index appeared to be the most sensitive measure in differentiating infant groups according to body size. In general neonatal body size appears to have a slight, although non-significant influence on the vocal F_0 of crying in healthy full term infants. Any body size related changes in cry F_0 are likely to be found for maximum F_0 and may reflect stress-related variations in nervous system activation.

Key words: acoustic analysis, cry, fetal growth, infants, fundamental frequency

Introduction

There has been a persistent conviction by researchers that an infant's cry can provide the basis for early diagnosis of health abnormality.[1] Well over 100 articles have been published since the early 1940s demonstrating that various risk factors are correlated with acoustic features of infant crying.[2] A frequently used measure to evaluate infant crying is vocal fundamental frequency (F_0). Vocal F_0 is a measure of the general mode of vocal fold vibration and is assumed to be dictated by the length, mass, and stiffness of the vocal folds.[3] The early vocal behaviors produced by young infants are predominantly laryngeal, with minimal supra-laryngeal involvement.[4] Therefore, F_0 is a suitable vocal parameter to evaluate during the infancy period.

Since F_0 is inversely related to the size of the sound source, physical size presumably plays an important role in determining vocal F_0.[5] Among normally developing infants and children, measures of body weight and body height are found to correlate grossly with the F_0 of their vocalizations.[3] There is further evidence to suggest that the relationship between physical size and F_0 can be found in infant crying, as well. Infants of questionable health status who are of low birth weight have been found to produce cries with significantly higher F_0 compared to healthy children of normal birth weight.[6-10] Such findings would suggest a simple, yet robust relationship between cry F_0 and basic features of physical size.

Vocal F_0 can be manipulated to communicate a variety of intentions and emotions, and these manipulations are not simply a reflection of physical size but, rather, neuro-physiological processes.[11] While it is not surprising to find F_0 manipulations in the speech of older children and adults, there is a growing body of research indicating that early infant crying involves processes of neuro-physiological control. For example, Wermke et al.[12] found F_0 variation of less than one semitone in individual infants during the first few months of life. The low level of variability was taken to suggest the existence of an already well-developed kinesthetic/auditory-motor feedback system to control processes in F_0 production. Gilbert and Robb[13] performed a longitudinal examination of hunger cries in four healthy infants across the first 12 months of life. The researchers identified a slight increase in cry F_0 during the course of the study. The monthly rise in F_0 was assumed to reflect a child's gradual control over crying to signal needs and wants (e.g., food). In spite of a presumably increasing size of laryngeal anatomy, which would tend to favor a lowering in F_0, infants used an elevated F_0. Lind and Wermke[14] examined natural spontaneous cries in one healthy infant across the first 3 months of life. Based on weekly sampling of the infant's cries, the researchers found minimal change in F_0. Lind and Wermke suggested that the lack of change in F_0 during the period of observation was a result of neuro-physiological influences, whereby infants maintain control over F_0, in spite of changes in laryngeal growth. Finally, Baeck and de Souza[15] recently examined the hunger cries of 30 healthy infants between the period of birth and 6 months of life and found essentially no change in F_0. The researchers stated that although both anatomical and neurological factors affecting F_0 are active during infant development, neurological influences were most dominant. Studies such as those profiled above imply that cry F_0 is relatively independent of various human body size (i.e., anthropometric) indices of infant growth and reflects a unique physiological behavior for establishing the building blocks of later, meaningful communication.

In spite of the evidence suggesting that F_0 may not be linked exclusively to physical size, there is limited research directly examining the relationship between cry F_0 of healthy neonates and basic anthropometric indices of human growth. Over 25 years ago, Zeskind and Lester[16] examined the crying behavior of neonates with differential fetal growth in response to a painful stimulus. A total of 57 healthy, full term 2-day-old neonates were sampled and characterized by their body proportion using the Ponderal index (PI). The PI is based on the Rohrer[17] index that quantifies the relationship between the amount of soft tissue mass to skeletal development by calculating the ratio of birth weight to birth length cubed.[18] Popularized by Miller and Hassanein,[19] this index has been used to characterize fetal growth and to identify growth retarded neonates in clinical practice.[18, 20-22] Neonates yielding a very low or high PI are assumed to show asymmetric fetal growth, with birth weight and/or birth length affected.[23] A normal PI is indicative of symmetrical growth in both weight and height.

Zeskind and Lester[16] found infants at the low and high ranges of PI to produce pain cries with a significantly higher mean F_0 compared to infants in the average PI range. Both low and high PI infant groups produced an almost identical mean F_0 (low PI = 665

Hz, high PI = 664 Hz), which was approximately 177 Hz above the F_0 value of the average PI group. A similar result was reported by Zeskind,[24] who investigated the non-pain cries of 39 two-day-old healthy neonates undergoing Neonatal Behavioral Assessment Scale[25] examination. The infants were also categorized according to PI. The infants in the low and high PI groups were found to produce a maximum F_0 that was twice as high as that of the average PI group (about 1000 Hz in both extreme groups compared to the average group F_0 of 524 Hz). The conclusion reached in both of these studies was that cries with an unusually high F_0 could serve as a risk marker for infants showing anthropometric signs of either retarded or accelerated fetal growth. However the conclusion reached by these researchers appears to disregard the possible relationship between vocal F_0 and body size, at least in regard to the low PI infants. The high mean F_0 demonstrated by the low PI group is perhaps not surprising when considering these infants were likely to have the smallest overall vocal anatomy. Therefore, it is difficult to assign an at-risk status to these infants. On the other hand, the high F_0 demonstrated by the high PI group is unusual because these infants likely possessed a large vocal anatomy. The findings for the high PI group support the suggestion that F_0 may not be linked exclusively to body size.

The relationship between infant cry and physical size is far from clear. It is important to clarify this relationship, especially when considering that a number of infant behavioral assessment scoring systems involve the collection of cries (e.g., CRIES[26]; NIPS[27]; NAPI[28]; PAIN[29]; Bernese Pain Scale for Neonates[30]). Newborns possess a rich and complex set of behaviors for regulating their internal biological state, as well as for exchanges with their environment. Although infants may not begin producing language until their first birthday, they are born ready to communicate with a rich vocabulary of body movements, visual responses, and cries. If the pitch (i.e., F_0) of cries is to be used as a key parameter in infant behavioral assessment, it is imperative to determine whether features of an infant's body size affect cry F_0.

Past research suggesting independence in cry F_0 from anthropometric indices has been based on examining infants across broad age spans, ranging from two weeks of life to 12 months of age.[13-15] None of these studies exclusively examined the cries of neonates during the first week of life. In addition, these past studies have not directly examined the relationship between body size and cry F_0. Accordingly, the present study was designed to perform a large scale evaluation of the F_0 of spontaneous cries produced by healthy full term neonates during the first week of life. The research question posed in this study was, *Is the F_0 of spontaneous cries is affected by features of body size?*

Method

Participants

A total of 131 healthy full term neonates (59 females, 72 males) served as the sample of participants. All infants were born at the Children's Hospital Lindenhof in Berlin, Germany spanning period of 2-years. The major inclusion criteria were, no prenatal complications, a normal birth history and delivery, gestational age range from 37 to 42 weeks, and normal Apgar scores. The mean Apgar scores ranged from 8-10 at one-minute and from 8-10 at five-minutes. Healthy neonates who were either small for gestational age (SGA) (i.e., below the 10th percentile of birth weight-for-gestational age) or large for gestational age (LGA) (i.e., above the 90th percentile) were included to ensure that a wide range of fetal growth was sampled. From the sample of 131 neonates, 19 were SGA (10 females, 9 males) and 3 were LGA (all males). Subsequent data analysis involved examining the group of neonates both with and without the SGA and LGA neonates included. Anthropometric features of body length (cm), body weight (gm) and head circumference (cm) were obtained for each infant at the time of birth. The same pediatrician was involved in making the measurements for each infant so as to ensure consistency in data collection. The local hospital institutional review board approved the study an informed consent was obtained from each of the 131 mothers.

Body size indices (BI)

To allow for close inspection between cry F_0 and body size, three indices of body composition and fetal growth were calculated for each neonate.

(1) *Ponderal Index* (PI) – defined as the ratio of body weight (g) to the cube of body length (cm^3) x 100.[17] The formula for calculation of PI was the same used by Zeskind and Lester[16] and Zeskind,[24] which allowed for post hoc comparison to the present findings.

(2) *Birth Weight:Length Ratio* (BW/L) – defined as the simple ratio of birth weight (g) to length (cm). The BW/L ratio has been advocated by Schneider and Schneider[31] and Tsou Yau and Chang[32] as being more reliable than PI to indicate body fatness and fetal growth retardation.

(3) *Birth Weight* (BW) – defined as the weight (g) of the neonate at the time of delivery. Haggarty et al.[33] demonstrated that body weight alone was a better predictor of anthropometric ratios and organ asymmetry than PI, and, moreover, that the inclusion of any other power of body length term generally did not improve on the use of weight alone.

On the basis of the various BI calculations, neonates were placed into one of three percentile sub-groupings, grossly reflecting low, average, and high fetal growth. In each of the three BI measures, the low subgroup consisted of neonates who yielded a score below the 25th percentile. The high subgroup contained neonates who yielded a BI score above the 75th percentile. Infants whose BI score fell within the range of the 25th to 75th percentile were classified as average. The percentile ranks for all three BIs were determined by normative percentiles for German neonates between 37-42 weeks gestational age, established by Landmann et al.[22] for PI, and by Voigt et al.,[34] for BW/L and BW, respectively.

Cry recording and signal analysis

Digital cry recordings were made an isolated carpeted room in a quiet environment within the hospital during the first week of life. The noise level in the room was perceptually judged to be low in ambient noise and acceptable for audio recording. The cry recordings were made using a DAT-recorder (SONY TCD-D3) coupled to a handheld directional microphone (SONY S220). Cry recording began when an infant started to fuss or at a time when the mother would normally feed the child. None of the cries were associated with the administration of a painful stimulus to the infant. Sampling frequency was 48 kHz and the dynamic range was 16 bits. The microphone was positioned approximately 10 cm from the infant's mouth. Only non-pain, spontaneous cries were considered in the analysis. Lester[35] defines spontaneous cries as a subset of hunger cries that are not restricted to an elicitation by hunger. The average duration of each infant's crying episode was approximately 2-minutes. Individual cry utterances comprising the crying episode were measured for F_0. A cry utterance was defined as the acoustic activity occurring on a single expiration. Cry utterances that contained harmonic distortions and/or phonatory noise (dysphonation) were excluded from the analysis to avoid artefacts in F_0 determination. A total of 1350 cry utterances obtained across the 131 infants were acoustically analyzed.

Measurement of cry F_0 was carried out using a CSL-Speech 4400/ MDVP acoustic analysis system (KAY Elemetrics Corp. /USA). Cry sequences were displayed on a computer monitor and the onset and offset of single expiratory cry utterances were demarcated using a pair of vertical cursors. The cry utterances were then low-pass filtered (Gaussian-filter) with a cut-off frequency of 40 Hz to eliminate outliers and artefacts (for details see Wermke et al.[12]). Following the filtering procedure, narrowband spectrograms were produced for all recorded cries. To avoid artifacts because of errors in pitch determination of noisy segments, the statistical data of the cry parameters were calculated only for harmonic signals. A vertical cursor was tracked across the harmonic structure of each cry utterance and the CSL software provided the the minimum, maximum, and mean F_0. Each measure was considered important in the present analysis to investigate whether cry F_0 is linked to body size, particularly F_0 values reflecting end-points of the crying continuum. Specifically, minimum F_0 is known to closely correspond to the general size characteristics of the larynx, particularly the length of the vocal folds.[36,37] Accordingly, minimum F_0 was assumed to most likely be affected by differences in body size corresponding to laryngeal size. Maximum F_0 is thought to be linked to neurological control that coordinates respiratory-phonatory activity, in addition to vocal fold size. There are several reports which tend to confirm that conditions involving neurological dysfunction/damage in infants result in an unusually high maximum F_0.[38-42] Therefore, if maximum F_0 was found to significantly differ between neonates of various body sizes, while minimum F_0 was fairly constant, it was assumed that mechanisms primarily related to nervous system functioning were involved.

Statistical analysis

In order to determine whether F_0 differed according to body size, a series of one-way analysis of variance (*ANOVA*) tests were performed for the three fetal growth subgroups comprising each BI. The data for the significance testing were based on first averaging the F_0 values of each infant's individual cry utterances. An infant's mean values were then averaged for the entire group of infants belonging to each BI sub-grouping. Separate *ANOVA*s were performed for each acoustic measure (minimum, mean, maximum F_0) for all three body size indices. In addition, *ANOVA*s were performed for each of the individual anthropometric features to determine whether they differed according to BI grouping. Instances when a significant result occurred were accompanied by follow-up paired *t*-tests or Mann-Whitney U tests, depending on distributional characteristics of the data.

Results

Anthropometric measures

The values for the various anthropometric measures, organized according to the three body size indices, are listed in Table 1. The calculated BI values established for the low, average, and high sub-groupings were found to differ significantly for each of the body size indices ($p < .01$). Birth weight was also found to differ significantly across each sub-grouping according to each BI ($p<.05$). Birth length differed significantly between the average and high sub-groups for both PI and BW/L groupings, and differed significantly between all three sub-groups for BW. Head circumference differed significantly between neonates in the three sub-groups for BW/L and for BW ($p<.05$), and differed between the low and high PI sub-groups. The significant differences in BI values were taken as confirmation that the fetal growth of the infants comprising each sub-grouping was sufficiently different to allow for examination of cry F_0.

F_0 measures

The values for each F_0 measure according to BI are listed in Table 2. The results for minimum F_0 indicated a slight pattern of decreasing F_0 as a function of increasing body size. However, ANOVA testing for minimum F_0 indicated no significant difference across the low, average, and high sub-groupings for each body size index. The minimum

F_0 data were reanalyzed upon removal of the SGA and LGA neonates, and resulted in similar ANOVA findings. A pattern of decreasing F_0 according to body size was also found for mean F_0. Results of ANOVA testing for mean F_0 closely paralleled those for minimum F_0, with the exception of the BW index, whereby low BW neonates had a significantly higher mean F_0 compared to high BW neonates ($p<.05$). The same results were obtained upon removal of the mean F_0 results for SGA and LGA neonates. The most marked difference between neonates was in regard to maximum F_0. For both BW/L and BW indices, neonates in the low group had a significantly higher F_0 compared to the high group ($p<.05$). The maximum F_0 of the high group was also significantly higher compared to the average group according to the BW index ($p<.05$). Similar overall results were obtained for maximum F_0 when the results for the SGA and LGA neonates were removed from the data set.

Discussion

In general, the anthropometric measures obtained for the neonates, organized according to the three body size indices were indicative of clear difference between the subgroups of children. Among the three BI measures, BW appeared to be the strongest indicator of growth differences across low, average, and high fetal growths. Birth length and head circumference were also found to clearly differ between all three fetal growth groups according to the BW index. While the PI and BW/L indices were useful in differentiating neonates according to body weight, they were less useful separating neonates according to birth length and head circumference. The conclusion that the BW index provided the best overall classification of body size supports the results of previous researchers, who have found the Rohrer PI to provide a less-than-ideal classification of growth symmetry compared to a simple ratio of body weight to body length.[33, 43-46] Still, others have questioned whether the inclusion of any power of body length term (e.g., BW/L) improves in differentiating fetal growth compared to the use of birth weight alone.[33] Our results are in good agreement with the suggestion that BW is sufficient for differentiating neonates of varying fetal growth.

The F_0 results obtained for the neonates according to PI indicated no statistical differences in any of the cry measures, although there was a noticeable trend towards decreasing F_0 with increasing fetal growth. The present findings differ from Zeskind and Lester[16] and Zeskind,[24] who found low and high PI neonates to produce cries with a significantly higher F_0 compared to neonates with an average PI. The researchers concluded that the F_0 of cries may reflect the risk status of neonates with signs of retarded or accelerated fetal growth. A likely reason for the difference between the present study and these past studies concerns the fetal growth characteristics comprising the low and high PI groups. The mean PI values reported by Zeskind and Lester[16] for their low and high subgroups were 2.05 and 3.07, respectively. The PI values of the present group of neonates in the low and high subgroups were 2.21 and 2.76 respectively. The PI categorization used by Zeskind and Lester[16] (as well as Zeskind[24]) falls well outside the cut-off levels (PI <2.2 & >3.0) recommended by Miller and Hassanein[19] for acceptable fetal growth. There is considerable evidence to suggest that infants whose PI falls within the extreme ranges of fetal growth are likely to be at high risk of neuro-developmental deficits.[47-49] Thus, one cannot rule-out the possibility that the high F_0 demonstrated by infants in these earlier studies was indicative of existing neuro-developmental problems. Further evidence of this likelihood can be garnered by examining the F_0 variability results reported by Zeskind and Lester[16] and Zeskind.[24] The standard deviation surrounding the mean and maximum F_0 values for the low and high PI infants exceeded 200 Hz, and in some cases exceeded 600 Hz, which is the same order of magnitude as the mean F_0 values. The neonates investigated in our study were all healthy and selected on the basis of medical inclusion criteria of prenatal and postnatal development. None of the neonates showed signs of developmental disorder. As shown by the present results, healthy neonates of differential growth (according to PI) do not necessarily differ in regard to the F_0 of their cries. If they do, the trend is toward a simple (inverse) relationship between F_0 and body size.

It is interesting to consider the F_0 results in regard to the BW classification scheme. While the BW index appeared to provide the most sensitivity in differentiating various features of fetal growth, the index also provided the most sensitivity in regard to cry F_0. Specifically, maximum F_0 was found to differ significantly according to BW. Neonates of high fetal growth produced cries that were significantly lower in maximum F_0 compared to neonates of low and average fetal growth. While this finding appears to support the suggestion that body size has an influence on the F_0 of neonatal crying, it is important to consider these results in comparison to those for minimum F_0. Recall that minimum F_0 closely corresponds to the general size characteristics of the larynx.[36,37] Therefore, minimum F_0 was assumed to most likely be affected by differences in body size corresponding to laryngeal size. This was not the case in the present study. The effect of decreasing F_0 with increasing body size was least robust for minimum F_0. Thus, the observed differences in maximum F_0 between infants of differing fetal growth may be linked to processes of nervous system functioning, in addition to anatomical size. Furlow[40] and others[41,42,50,51] have inferred that crying maximum F_0 is reflective of neuro-physiological processes regulating vocal fold vibratory behavior. Accordingly, the large F_0 differences observed across the neonates of differing fetal growth could indicate possible differences in nervous system activity controlling cry. That is, neonates of smaller body size may simply have experienced more stress during the crying episode compared to larger neonates. The increase in stress was reflected in their crying as a high maximum F_0.

In summary, past cry studies have suggested that healthy, full term infants exhibit neuro-physiological control over cry F_0, in spite of developmental changes in laryngeal growth.[12-15] These studies are based on systematic examination of infants between the ages of two-weeks and 12-months of life. The present study was confined to the crying behavior demonstrated by neonates during the first week of life. Across the group of neonates, the relationship between body size and F_0 was not strong, and therefore provides marginal support for the original prediction that F_0 features of neonatal crying may be affected by physical size. Only upon consideration of the extreme range of crying, namely maximum F_0, can neonates be clearly differentiated on the basis of body size. For now, we feel that F_0 measures can be applied to the cries of full term neonates without running the risk of data misinterpretation resulting from body size differences. However, researchers who use cry F_0 to examine infants of unusual body size (e.g., preterm, very low birth weight), should take caution, so as to avoid confusing simple growth influences on cry F_0 from possible nervous system disturbances.

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