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# Assessment of Infant Cry: Acoustic Cry Analysis and Parental Perception

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Infant crying signals distress to potential caretakers who can alleviate the aversive conditions that gave rise to the cry. The cry signal results from coordination among several brain regions that control respiration and vocal cord vibration from which the cry sounds are produced. Previous work has shown a relationship between acoustic characteristics of the cry and diagnoses related to neurological damage, SIDS, prematurity, medical conditions, and substance exposure during pregnancy. Thus, assessment of infant cry provides a window into the neurological and medical status of the infant. Assessment of infant cry is brief and noninvasive and requires recording equipment and a standardized stimulus to elicit a pain cry. The typical protocol involves 30 seconds of crying from a single application of the stimulus. The recorded cry is submitted to an automated computer analysis system that digitizes the cry and either presents a digital spectrogram of the cry or calculates measures of cry characteristics. The most common interpretation of cry measures is based on deviations from typical cry characteristics. Another approach evaluates the pattern across cry characteristics suggesting erarousal or underarousal or difficult temperament. Infants with abnormal cries should be referred for a full neurological evaluation. The second function of crying—to elicit caretaking—involves parent perception of the infant's needs. Typically, parents are sensitive to deviations in cry characteristics, but their perception can be altered by factors in themselves (e.g., depression) or in the context (e.g., culture). The potential for cry assessment is largely untapped. Infant crying and parental response is the first language of the new dyadic relationship. Deviations in the signal and/or misunderstanding the message can compromise infant care, parental effectiveness, and undermine the budding relationship.



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**Key Words:** cry analysis; cry acoustics; neurological status and cry; *in utero* substance exposure and cry; medical conditions and cry; computer analysis of cry; temperament; reactivity; regulation; cry perception; fundamental frequency of infant cry

"Crying is a biological siren, alerting the caregiving environment about the needs and wants of the infant and motivating the listener to respond." [Zeskind and Lester, 2001, p 149]. There are two key aspects of cry (1) the cry itself, which is innervated by the cranial nerves modulating the autonomic nervous system and signals emergency status, and (2) the salience of the cry to any potential caretakers in the environment, producing a visceral reaction that compels action. Infant cries have both infant and caretaker in a state of strong sympathetic nervous system activation. This state is commonly described as the "fight or flight" response; except in this case only the caretaker can take action. "Unresponsible" potential caretakers may take flight or distance themselves from the crying infant (e.g., avoidance of a crying infant in supermarket) while "responsible" potential caretakers "fight" to stop the crisis by alleviating the infant's distress, which turns off the siren. Thus, cry is not just an infant behavior, but rather it is a part of a behavioral system in the human species that assures survival of the helpless neonate by eliciting others to meet basic needs. The process underlying the behavioral system can be disrupted in two general ways. First, the cry signal may be poor or atypical. Second, the caretaker may have atypical reactions to the cry, including both under- and overresponsiveness. Either situation can compromise the effectiveness of the behavioral system. The most extreme case is "shaken baby syndrome" in which aversive cries trigger aggression toward the infant rather than toward the reason the infant is crying [Frodi, 1985]. The next section describes the physiology of infant cry and identifies cry characteristics and their source.

## THE SIGNAL

Infant crying comprises a rhythmic alternation of cry sounds (utterances) and inspiration. Crying is part of the expiratory phase of respiration with sound or phonation produced by the larynx, which contains the vocal cords or folds and the glottis (opening between vocal folds). The larynx has three functions: swallowing, breathing (glottis is fully open), and voice production (glottis is closed). When air is forced through ad-

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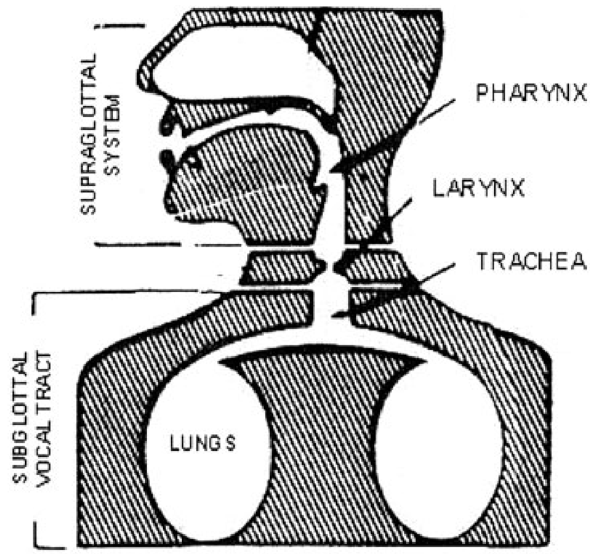


Fig. 1. The anatomy of cry.

ducted (closed) vocal cords, the increased air speed due to passage through a constricted tube (Venturi tube effect) results in a drop in air pressure (the Bernouilli principle), causing the vocal cords to open and close rapidly (approximately 250 to 450 Hz or cycles per second in normal, healthy newborns). This vibration is the fundamental frequency (f0) and is heard as the pitch of the cry. The lower vocal tract (see subglottal vocal tract and larynx in Fig. 1) is closely associated with the autonomic nervous system. In addition to f0, the lower vocal track produces sound characteristics such as loudness, and the rhythm of expiratory cry sounds and inspiration, which includes inhalation as well as breath holding. The sound from the lower vocal tract is modified by the size and contour of the upper vocal track (supraglottal system). The upper vocal tract shapes the sound to produce resonant frequencies or formants (frequency bands above f0) similar to a sound chamber of a musical instrument, which makes it easy to distinguish, say, a C note from a piano versus a guitar. The infant vocal tract is smaller than the adult vocal track. Further, the shape of the newborn's vocal tract is more like a chimpanzee than a human adult with the larynx positioned higher in the vocal track subsequently dropping to the adult position in the vocal track beginning at 6 months and achieving adult positioning by 2 years of age [Laitman et al., 1978; Laitman and Crelin, 1980].

## NEUROLOGICAL BASIS OF CRY

Neonatal cry arises from aversive internal or external stimulation and is produced by coordination among several brain regions, including the brainstem, midbrain, and limbic system. The lower brain stem controls the muscles of the larynx, pharynx, chest, and upper neck through the vagal complex (cranial nerves 9 to 12) and the phrenic and thoracic nerves [Lester and Boukydis, 1990]. Variation in tension on the larynx muscles, cricothyroid and vocalis, and the abdominal respiratory muscle are thought to be responsible for f0. There are three identifiable cry modes of vocal fold vibration: basic cry or phonation or fundamental frequency (f0), high pitch cry or hyperphonation (1000–2000 Hz), and noisy or turbulent cry (dysphonation) [Lester, 1984; Golub, 1989]. Damage in the vagal cranial nerve complex is related to atypical patterns of f0. Rapid shifts or variability in f0 suggests instability in the neural control system. The brainstem also controls the contour and cross-sectional airway of the supraglottal system, which shapes formant frequencies. Only the first two formants are usually measured: The first formant (F1) occurs at approximately 1100 Hz and the second formant (F2) at approximately 3300 Hz [Lederman et al., 2004].

Other regions of the brain participate in cry initiation (limbic system, hypothalamus), configuration of the cry pattern (midbrain), and motor coordination of respiration, larynx, and articulation (reticular activating system) [Zeskind and Lester, 2001]. The extensive vagal innervation and central nervous system (CNS) coordination underlying infant cry result from modulation by the autonomic nervous system. Cry initiation, including latency to cry or threshold (amount of stimulation required), has been associated with sympathetic arousal. Respiratory modulation and temporal patterning of the cry (long or short duration of cry utterance, number of utterances, duration of inspiratory period, and number of short unvoiced sounds or utterances) reflect parasympathetic mechanisms of homeostasis. Modulation of the overall contour of f0 as well as the amplitude or intensity of the cry reflects both faciliatory and inhibitory autonomic mechanisms [Lester, 1984]. Table 1 provides a quick reference for cry characteristics currently used in infant assessment [Corwin et al., 1996; Zeskind and Lester, 2001; Lester et al., 2002]. The first four characteristics evaluate the entire cry (Cry Latency to Short Utterances); the remaining characteristics are calculated for each cry utterance and may be averaged across utterances.

## HISTORY OF ASSESSMENT OF INFANT CRY

Early research on assessment of infant cry (1960s–1980s) examined cries of infants already diagnosed with medical conditions related to neurological damage. Neonatal cries were frequently targeted because they reflect initial neurological state prior to possible shaping by experience. Further, the assessment of pain cries was favored to provide the clearest picture of the infant's capacity to signal emergency. Early studies used spectrographic analysis, which provided a picture of the cry from which a limited number of acoustic characteristics could be derived. Visual patterns from the spectrograph were often described but these characteristics have not proven to be reliable and some may in fact be artifacts of the technology. Table 2 lists these studies by medical condition and associated cry measures indexed by acoustic features (visual descriptions of spectrographic patterns are not included). These studies support the relationship between neurological status and cry. The f0 is particularly sensitive to neurological insult with both higher levels overall and greater variability. Noise concentration or dysphonation is noted in only one study, thus transient conditions in the postpartum period that may have caused a noisy cry cannot be ruled out. While these studies confirm brain insult, they do not appear to offer new diagnostic information, as the medical conditions are already known. Two exceptions are the studies of infants with severe asphyxia or bacterial meningitis. Asphyxiated infants with the most abnormal cries had the

**Table 1. Cry Characteristics and Associated Mechanism**

| Characteristic | Definition | Biological Mechanism |
|---|---|---|
| Cry Latency | Time from known stimulus to onset of the first utterance (cry sound) | Arousal from limbic–hypothalamic system |
| Threshold | Number of applications of stimulation to elicit a cry | Arousal from limbic–hypothalamic system |
| Utterances | Number of cry sounds across cry | Neural control of respiratory system |
| Short Utterances | Number of unvoiced sounds across cry | Unstable respiratory control |
| Phonation | Cry mode resulting from vocal fold vibration between 350 and 750 vibrations or cycles per second (Hz) | Neural control of muscular tension in vocal folds and air flow through the glottis |
| Hyperphonation | Cry mode caused by a sudden upward shift in f0 to >1000 Hz | Neural constriction of the vocal tract |
| Dysphonation | Cry mode caused by noisy or inharmonic vibration of the vocal folds | Unstable respiratory control |
| Cry Mode Changes | Number of times cry modes change during an utterance | Instability in neural control of the vocal tract |
| Fundamental frequency (f0) | Base frequency during vocal fold vibration, heard as the pitch of the cry | Vagal input to larynx and lower vocal tract |
| First Formant | Frequencies centered at first resonance of f0, approximately 1100 Hz | Neural control of size and shape of upper vocal tract |
| Second Formant | Frequencies centered at second resonance of f0, approximately 3300 Hz | Neural control of size and shape of upper vocal tract |
| Duration | Time (ms) from onset to offset of cry utterance. | Neural control of respiratory system |
| Duration of Inspiration (Interutterance Interval) | Time (ms) between cry utterances, which is a measure of breath holding is evaluated by the 2$^{nd}$ inspiratory period | Neural control of respiratory system |
| Amplitude | Intensity of the cry (dB). Heard as loudness. | Neural control of respiratory system and capacity |
| Variability in f0 | Changes in f0 | Instability in neural control of the larynx and lower vocal tract |
| Variability in F1, F2 | Changes in formant | Instability in neural control of upper vocal tract |
| Variability in Amplitude | Changes in intensity within an utterance or averaged across utterances | Instability in neural control of the respiratory system |

**Table 2. Association of Cry Characteristics with Severe Medical Conditions via Sound Spectrogram**

| Medical Condition | Study | Cry Measure |
|---|---|---|
| Asphyxia | Michelsson, [1971]; Michelsson et al., [1977a]; Partanen et al., [1967] | ↑ f0, ↑ f0 instability (biphonation), ↑ subharmonic break, ↑ or ↓ duration |
| Brain damage | Fisichelli and Karelitz, [1966]; Karelitz and Fisichelli, [1962]; Sirviö and Michelsson, [1976]; Wasz-Höckert et al., [1968] | ↑ f0, ↑ f0 instability (biphonation), ↓ duration, ↑ threshold, ↑ latency, ↑ short utterances |
| Cri-du-chat | Vuorenkoski et al., [1966]; Wasz-Höckert et al., [1968] | ↑ f0 |
| Down syndrome | Fisichelli and Karelitz, [1966]; Wasz-Höckert et al., [1968] | ↓ f0, ↑ f0 variability, ↓ intensity (amplitude) |
| Hydrocephalus | Michelsson et al., [1984] | ↑ f0, ↑ f0 instability, ↑ latency |
| Hypothyroidism | Michelsson and Sirviö, [1976] | ↓ f0 |
| Krabbe's Disease | Thodén and Michelsson, [1979] | ↑ f0, |
| Meningitis (Bacterial) | Michelsson et al., [1977b] | ↑ f0, ↑ f0 instability (biphonation), ↓ duration |
| Trisomy 13, 18, 21 | Michelsson et al., [1980]; Lind et al., [1970]; Ostwald et al., [1970] | ↓ f0 |

poorest prognosis [Michelsson, 1971; Michelsson et al., 1977a]. Infants with bacterial meningitis and more atypical cries tended to have neurological sequelae at follow-up (4 to 18 months later) [Michelsson et al., 1977b]. Although these results open the door to using cry analysis to predict individual differences in outcomes for neurologically involved infants, no additional work has been done.

The most notable application of cry analysis to predict future morbidity in normal infants is the search for an early marker for sudden infant death syndrome (SIDS). This research differs from studies of infants with known medical conditions in that there are no other concurrent clinical signs. Table 3 lists the studies of cry and SIDS. Overall, the most consistent pattern of results associated with SIDS is high F1 and more mode changes, suggesting constriction of the upper vocal track and instability in neural control of the vocal tract. The largest, prospective study of SIDS ($n$ = 21,880 healthy term newborns with 12 SIDS deaths) by Corwin and associates [1995], found the combination of high F1 and increased mode changes across multiple cries increased the risk for SIDS 32 times. Infants who died of SIDS showed these cry characteristics (high sensitivity for SIDS). Unfortunately, many children showed these cry characteristics but did not die from SIDS (low specificity). Thus, while providing further proof that neonatal cry characteristics are linked to atypical neurological function even when no other symptoms are present, the high false positive rate limited the application of these findings during routine medical exams.

In addition to frank neurological damage, many of the early researchers also examined cry characteristics in in-

**Table 3. Cry Characteristics Associated with SIDS**

| Study | Cry Characteristics via Sound Spectrogram | Study | Cry Characteristics via Computer Cry Analysis |
|---|---|---|---|
| Stark and Nathanson [1975] | Shorter cry utterances, lower amplitude, more high and extremely high f0 events with rapid shifts | Golub and Corwin, [1982]; Corwin et al., [1986] | ↑ F1 |
| Colton and Steinschneider, [1981] | ↓ f0, F1, F2, ↑ utterance duration, ↑ sound pressure, episodes of F1 >2000 Hz and F2 at 4000 Hz | Corwin et al., [1995]; Hoffman et al., [1988] | ↑ F1, ↑ mode changes |

**Table 4. Cry Characteristics Associated with Potential Central Nervous System Insults**

| Medical Condition | Study | Cry Characteristics |
|---|---|---|
| Low birth weight (<2500 g), small for gestation | Michelsson, [1971] | ↑ duration, ↓ f0 |
| Low birth weight (<2500 g), prematurity | Michelsson, [1971] | ↑ f0, ↑ f0 instability (biphonation) |
| Prematurity | Michelsson et al., [1983] | ↑ f0, ↓ duration |
| Preterm infants | Lester, [1987] | ↑ f0, ↑ f0 variability, ↓ F1 variability, ↓ amplitude associated with ↓ BSID (18 mo)<br>↑ f0 variability, ↑ F1, ↓ amplitude with ↓ cognitive scores (McCarthy, 60 mo) |
| Preterm infants | Corwin et al., [1992] | ↑ short cry utterances with ↓ developmental outcome (30 mo) |
| Hyperbilirubinemia | Koivisto, et al., [1970] | ↑ f0, ↓ duration, ↓ latency, ↑ f0 instability (biphonation and bifurcation) |
| Hyperbilirubinemia | Wasz-Hockert et al., [1971] | ↓ latency, ↓ duration, ↑ f0, ↑ f0 variability |
| Hyperbilirubinemia | Golub and Corwin, [1982] | Unstable glottic function [mode changes] |
| Hyperbilirubinemia | Vohr et al., [1989] | ↑ F1 variability, ↑ phonation |
| Lead exposure | Rothenberg et al., [1995] | Low % nasalization, ↓ number of cries, ↑ f0 |
| Prenatal opiate exposure | Blinick et al., [1971] | ↑ f0, increased likelihood of abnormal cries |
| Prenatal opiate exposure | Corwin et al., [1987] | ↑ hyperphonation, ↑ short utterances, ↑ f0, ↑ duration of 1st cry utterance associated with withdrawal symptoms |
| Prenatal opiate exposure | Lester et al., [2002] | ↑ short utterances, ↑ hyperphonation |
| Prenatal cocaine exposure | Corwin et al., [1992] | ↓ cry utterances, ↑ short cry utterances, ↓ hyperphonation |
| Prenatal cocaine exposure | Lester et al., [1991] | Direct effects (excitation) ↑ duration, ↑ f0, ↑ F1, ↑ F1 variability; Indirect effects via growth retardation (depression) ↑ latency, ↓ utterances, ↓ amplitude, ↑ dysphonation |
| Prenatal cocaine exposure | Lester et al., [2002] | ↑ f0, ↓ F2, ↑ dysphonation, ↑ amplitude, ↑ duration 2nd utterance |
| Prenatal marijuana exposure | Lester and Dreher, [1989] | Shorter cries, ↑ dysphonation, ↑ f0, ↑ f0 variability, ↓ F1 |
| Prenatal marijuana exposure | Lester et al., [2002] | ↑ mode changes, ↑ F2 |
| Prenatal alcohol exposure | Nugent et al., [1996] | ↑ dysphonation, ↑ F1 |
| Prenatal alcohol exposure | Lester et al., [2002] | ↓ threshold, ↑ hyperphonation, ↓ F1 |
| Prenatal tobacco exposure | Nugent et al., [1996] | ↑ f0, ↑ F2, ↑ F2 variability |
| Prenatal methamphetamine exposure | LaGasse et al., [2004] | ↓ threshold, ↑ variability in f0, ↑ variability in amplitude, ↑ mode changes, ↑ dysphonation, ↑ short utterances, ↑ variability in dysphonation |

fants at risk for poor outcomes based on potential neurological insult including prematurity and hyperbilirubinemia. The recent generation of cry studies not only studied cries of infants who were premature or had hyperbilirubinemia, but also examined the effects of potential prenatal insult during pregnancy from lead exposure and exposure to drugs of abuse. Table 4 lists these studies and their findings. Overall, infants at medical risk show higher and more variable f0, lower amplitude, fewer utterances, but increased short utterances, suggesting increased tension and instability of neural control of the vocal tract and poorer control and capacity of the respiratory system. Overall, drug-exposed infants also show increased f0 and more short utterances. In addition, drug-exposed infants show a pattern of dysphonation (noisy signal), hyperphonation (extremely high pitch), increased mode changes from phonation to dysphonation, and variability of F1 and F2 (dysregulation), indicating poor neural control of the vocal track and respiration. Given the results of earlier studies relating cry characteristics to known neurological compromise, these findings suggest that at-risk infants have undetected neurological damage and that cry analysis may be able to identify these infants when no other symptoms are present.

Colic is a special case in which excessive crying is part of the clinical diagnosis [Lester, 1997]. The traditional definition of excessive crying in colic is based on the "rule of three" criterion (crying that lasts at least 3 hours per day, at least 3 times, at least 3 consecutive weeks) developed by Wessel [1954]. Other criteria include behavioral characteristics such as paroxysmal onset to crying bouts, hypertonia, and inconsolability as well as acoustic characteristics such as increased and more variable f0 and more dysphonation [Lester et al., 1992]. Although colic typically occurs in infants from 3 weeks to 3 months, these acoustic characteristics may precede the onset of colic itself, suggesting greater vulnerability to stress in these infants, which may be a precipitating condition in the development of colic.

Long-term implications of neonatal cry measures have been shown in premature infants [Lester; 1987; Lester et al., 1989b]. As shown in Table 4 (Preterm Infants), high f0, more variable f0, less variable F1, and amplitude predicted lower Bayley scores at 18 months and cognitive scores on the McCarthy Scales at 60 months. Unlike earlier studies of diagnosed neurological conditions, many of these studies analyzed cries with spectral analysis, including the CRI system (described under Description of Scoring System). The advantage of the new technologies is the level of specificity of atypical cry characteristics by risk condition. The disadvantage is summarizing findings in meaningful ways. This issue is discussed under Description of Scoring System.

## GOAL/OBJECTIVE OF TEST

Assessment of infant cry has two objectives: first, to detect potential neurological insult, and second, to detect atypical signals that could confuse or disrupt parent perception, making caretaking decisions more difficult and less effective. Evaluation of possible neurological insult should lead to a full neurological work up and early intervention. Evaluation of parents' misperception of their infants' cry signal should lead to intervention with the dyad to improve interpretation of signals that can facilitate effective parenting.

## DESCRIPTION OF TEST PROCEDURES

The cry test procedure is relatively naturalistic and noninvasive. In the procedure used by Lester and associates (CRI Research, Inc), the infant is placed in an isolette and maintained in a noncrying state for 30 seconds before the cry is elicited. A Marantz PMD201 cassette recorder and Radio Shack Dynamic Unidirectional Microphone are used to record the cry for 30 seconds following stimulation to the sole of the infant's right foot. If the infant does not cry, a second stimulus is applied. The infant is supine with the microphone suspended 5 inches above the infant's mouth. A specially designed stimulator and tone box automatically places a tone on the tape to coincide with the time of the cry stimulus. Cries can be recorded without the tone, but the latency from the stimulus to the first cry utterance cannot be accurately measured without the tone. A similar procedure used by Zeskind and others uses a rubber band snap, stretched a standard distance that elicits a 10-second cry [Zeskind et al., 1996]. If the infant does not sustain the cry for 10 seconds, another snap is applied, up to five applications. The essential features of both procedures are a standardized stimulus, a professional level recorder, and a microphone a fixed distance from the infant's mouth.

## DESCRIPTION OF SCORING SYSTEM

Current studies take advantage of advances in digital systems and software packages that analyze acoustic attributes. Two different scoring systems for infant cry are presented. First, there are relatively inexpensive software packages that are designed to analyze child and adult language. These programs produce digital spectrograms that yield quantitative information, point by point, based on the placement of the cursor on a specific location on the spectrogram image. While easy to implement, abstracting data by hand can be a laborious process. Further, these programs were not developed for the infant vocal tract. Thus, formant frequencies that depend on the upper vocal tract are difficult to locate on the spectrogram, calling into question the calculation of magnitude for F1 and F2. Recall that formants are the harmonic content of a sound produced by mouth shape and vocal cord length. The infant vocal tract is obviously different in size and shape from the adult vocal tract. While these programs are accurate, the need to select points by hand invites observer error. There is little reliability information reported using these techniques.

A second approach involves an automated computer analysis system used in several studies, which was designed specifically to perform infant cry analysis (Cry Research Inc., Brookline, MA) [Lester and Dreher, 1989; Corwin et al., 1992; Lester et al., 1992; Nugent et al., 1996]. This system is compatible with the first testing procedure described under Description of Test Procedures. Each 30-second cry signal is filtered above 5 kHz and digitized at 10 kHz by the cry computer. For each cry utterance (defined as a cry during the expiratory phase of respiration lasting at least 0.5 seconds), a Fast Fourier Transform is applied to compute the log magnitude spectrum for each 25-ms block of the cry utterance.

The automated cry system yields the following 17 cry variables describing the entire cry or each utterance: Cry Latency (interval in seconds, stimulus to cry onset); Threshold (number of stimuli to elicit a cry), number of Utterances (number of expiratory cry phonations that occurred during the 30-second recording), number of Short Utterances (number of expiratory cry phonations $<$ 0.5 seconds that occurred during the 30-second recording), Hyperphonation (average percent of 25-ms blocks with fundamental frequency $>$ 1000 Hz), Dysphonation (average percent of 25-ms blocks with turbulence (noise) or aperiodic sound), number of Cry Mode Changes (number of blocks that change between phonation and dysphonation), Fundamental Frequency or f0 (median frequency in Hz of vocal fold vibration, heard as voice pitch), and First Formant or F1 and Second Formant or F2 (median frequencies in Hz of the resonance frequencies that occur as a result of the filtering of the upper vocal tract), Duration (average length in seconds of the cry utterance), Inspiratory Period (interval in seconds between first and second cry utterance), and Amplitude (average energy in dB during an utterance). Also analyzed were Variability in f0, F1, F2, and Amplitude (interquartile range of each parameter). The investigator decides whether to use a specific utterance or to average across two or more utterances for variables pertaining to the utterance level (Hyperphonation to Variability variables above).

The reliability of the CRI system was examined by analyzing the same tape of 30 cries three times. The resolution of the utterance detection is 25 ms with a 2% error. The resolution of the FFT is 5–10 Hz with 1% error in the calculation of the acoustic measures [Lester et al., 1991]. Unlike software packages that perform acoustic analysis on sound and language, the CRI system is not commercially available at this time, limiting access to collaboration with current users.

## DURATION OF TEST/PROCEDURE

One of the advantages of the cry test is that it is brief, typically requiring less than 5 minutes, including preparation time.

## TRAINING REQUIRED

It should be noted that the cry test described here is conducted on a pain cry in part because pain cries represent the infants' "best" distress signal and the cry stimulus is known and standardized. However, any recorded cry could be submitted for acoustic analysis. Administration of the cry test requires little training. The tester must set up a space that is quiet and free from distraction during the test, place a microphone 5 inches from the infant's mouth, and maintain the child in a noncrying state prior to the test. Administration of the foot stimulator is automatic and requires only correct placement. Administration of the rubber band snap requires stretching the band the required distance and releasing it in the designated location on the child's foot (there is more room for error using the rubber band than the automatic stimulator). Further, the tester needs to have the recorder on from the onset of stimulation to the end of the recording time (30 seconds by the CRI system and 10 seconds by the rubber band snap).

Analyzing cry requires training on the specific system and expertise in interpreting the output. Uploading the digitized cry signal to the computer programs is fairly automated. The first method previously discussed using commercially available acoustic analysis software generates a digital spectrogram of the cry, but frequency and amplitude data are abstracted by hand point by point. Thus, data scoring overall is a very laborious process that invites observer errors. This process requires training to identify the datum of interest as well as further data entry and summarizing. The second method using the CRI system is designed to be fully automated when used with the cry collection device described above. This system automatically generates outcome variables. Many variables are generated for each utterance (there could be over 20 utterances in a 30-second cry) and expertise is needed to interpret these data, as there is no consensus on which utterance(s) to use or combine.

## SIGNIFICANCE OF TEST RESULTS

### Cry Signal

Despite differences in cry measurement, studies consistently point to high f0 or high pitched cries as a marker for potential neurological insult. Other markers associated with perinatal risk and prenatal insult include periods of hyperphonation or extremely high pitched cries, dysphonation or noisy, turbulent cries, as well as frequent mode changes between phonation and dysphonation, and variability in f0 and F1. The presence of one or more of these markers of poor neural control of the vocal tract or the respiratory system warrants further neurological evaluation.

There has been increased interest in identifying patterns across individual cry measures that tap into more global, enduring characteristics of the infant that have significance for subsequent development. In this section we identify some approaches that summarize across cry characteristics.

### Neurobehavioral Syndrome

In a sample of cocaine-exposed infants, Lester identified two distinct neurobehavioral syndromes based on the direct neurotoxic effects of cocaine, which are associated with excitable behavior and the indirect hypoxic effects associated with growth retardation and depressed behavior. Table 5 shows the cry variables associated with each syndrome [Lester et al., 1991]. The excitable syndrome includes cry measures indicating increased CNS reactivity, higher arousal, and greater tension in the vocal tract. The depressed syndrome associated with poor fetal growth indicates lower CNS arousal and decreased responsivity to the stimulus. Infants can show a mixed syndrome, but interpretation becomes more complex. The excitable/depressed syndrome typology has been successfully applied to neurobehavioral assessment, such as on the Brazelton exam [Brazelton et al., 1987] or the NICU Network Neurobehavioral Scale [Lester et al., 2002] in cocaine-exposed infants, supporting the notion of stable individual differences in response to stimulation [Tronick et al., 1996; Field et al., 2002].

**Table 5. Cry Characteristics Indicating Excitability and Depression**

| Excitability | Depression |
|---|---|
| ↑ Duration | ↓ Utterances |
| ↑ f0 | ↑ Latency |
| ↑ F1 | ↓ Amplitude (energy) |
| ↑ Variability in F1 | ↑ Dysphonation |

### Reactivity and Regulation

A second approach applies the constructs of reactivity and regulation to describe patterns of effects and to help deal with "mixed" symptoms. These constructs are indices of infant temperament, particularly well-articulated by Rothbarts' psychobiologic theory linking temperament to underlying autonomic processes [Rothbart et al., 1994]. One application of the constructs of reactivity and regulation to cry parameters is to categorize cry parameters by underlying biological processes into those measuring initial response to stimulation (reactivity) and those indicating regulatory processes of the respiratory system and the vocal track [Lester et al., 2002; LaGasse et al., 2003]. As shown in Table 6, either low or high reactivity can be atypical conditions, unlike poor regulation, which is usually unidirectional.

By folding cry acoustic analysis into the larger construct of temperament, the interpretation and implications of atypical cries are greatly facilitated. For example, an infant who cries at the first stimulus, but shows high f0, dysphonation, and many mode changes, shows appropriate reactivity, but poor regulation. This interpretation has two implications for intervention: first, it may help focus intervention toward scaffolding regulatory processes in the infant, rather than shielding the infant from overstimulation; second, this interpretation is understandable to parents, who may feel confused and even ineffective at soothing their infants. The advantage of cry analysis to the measurement of temperament is that cry can be measured earlier than standard measures of temperament, which are typically evaluated no sooner than 3 or 4 months of age.

Support for the link between infant cry and temperament was shown in a

**Table 6. Reactivity / Regulation by Cry Parameters**

| Atypical Reactivity | | Poor Regulation | |
|---|---|---|---|
| Low | High | Poor Respiratory Control | Poor Control of Vocal Track |
| ↑ Latency | ↓ Latency | ↓ Duration of Utterances | ↑ f0 |
| ↑ Threshold | | ↑ Inspiratory Period | ↑ F1 |
| | | ↓ Number Utterances | ↑ F2 |
| | | ↑ Number of Short Utterances | ↑ Hyperphonation |
| | | ↓ Amplitude | ↑ Mode Changes |
| | | ↑ Variability in Amplitude | ↑ Variability in f0 |
| | | ↑ Dysphonation | ↑ Variability in F1, F2 |

study of preterm infants, whose cries were recorded at 40 weeks' gestational age and whose mothers rated their temperament 9 months later on the Infant Characteristics Questionnaire [Lester and Boukydis, 1990]. The cries of infants rated as fussy and difficult had more hyperphonation and more variability on f0 than cries of easy infants. Similarly the cries of infants who had colic in this sample from 1 to 4 months of age showed increased hyperphonation and higher and more variable f0 and were rated by their mothers as more fussy and difficult than infants without colic [Lester et al., 1992]. In a study of term infants, factor scores derived from maternal ratings of temperament using the Infant Characteristics Questionnaire and the Infant Behavior Questionnaire at 4 months were compared with infants' cry acoustics during the neonatal period and at 4 months of age [Huffman et al., 1994]. Infants rated as more negative/irritable had cries with shorter duration, higher f0 and F2 at 1 week and higher f0 at 4 months. Infants rated as more negative/inhibited (unadaptable) had cries with shorter duration, less phonation (increased dysphonation), and higher f0 at 1 week and increased f0 at 4 months. Further, duration and f0 were stable from 1 week to 4 months, which provides new evidence that neonatal cry characteristics reflect individual differences in young infants.

Although the focus of this paper is on neonatal pain cries, infant cry acoustics after the neonatal period have been associated with temperament. Parents rated their infants as easy versus difficult on the Infant Characteristics Questionnaire at 4 to 6 months, and their infants' hunger cries were recorded at the same age [Bates et al., 1979; Lounsbury and Bates, 1982]. The cries of infants rated as difficult had increased f0 and frequent and longer pauses between utterances (similar to increased Inspiratory Period and increased Number of Short Utterances) than cries of easy infants.

It should be noted that there is question as to whether neonatal behavior is differentiated enough to distinguish reactivity versus regulation. For example, in a sample of term normal newborns, Zeskind found that a higher threshold of response (more rubber band snaps) was associated with disrupted autonomic regulation in heart rate rhythms and fewer startles and changes in behavioral states [Zeskind et al., 1996]. The association between low reactivity indexed by high threshold to cry and regulation indexed by heart rate or behavioral patterns could reflect less differentiation between reactivity and regulation in cry parameters than suggested by Table 6 or a complex interaction of reactivity and regulatory processes underlying heart rate patterns and behavior.

Given this concern, an alternative approach that is under consideration is to interpret all cry parameters in the first cry utterance as reactivity and consider change across utterances as regulation or recovery. The theoretical basis for this approach is the observation that cries across infants look more alike than different in the first utterance and in later utterances when the cry has dampened to a rhythmic but less urgent signal. Striking individual differences in response to a standard pain stimulus are more obvious in the second and third utterances and may reflect parasympathetic processes regulating the cry and restoring homeostasis (since the pain stimulus has not continued). This approach may be useful not only in distinguishing good regulators from poor regulators but also in linking dysregulated crying to caretakers' response. For example, if cry parameters particular aversive to parents (high f0, dysphonation) do not persist beyond a few seconds, parents are more likely to perceive their infants as "easy" babies. In keeping with the definition of a temperamental trait as a biological disposition that is relatively stable and enduring across context and time, highly reactive or underreactive infants who are also poor regulators (as identified from neonatal cry) may be more likely to have difficulty with behavioral regulation or inhibitory control during later infancy and childhood.

**Parent Perception**

What sets cry apart from other neonatal assessments? Like other assessments cry assessment is infant based, providing an early screen of the integrity of the nervous system. But infant cry also impacts the social context to elicit nurture necessary for survival. The appropriateness of the caretaking response should be related to the interpretation. Thus, cry should be viewed as a biosocial phenomenon that directly reflects the status of the nervous system and indirectly mediates development through parental intervention [Lester, 1984]. The best support for the biosocial model is in a study of preterm infants in which parents rated the aversiveness of an infants' cry [Lester et al., 1995]. Infants of mothers who correctly identified their infant's cry as aversive (increased f0) or as not aversive (normal f0) had higher Bayley mental scores and language scores at 18 months than infants whose mothers misperceived their infant's cry signal. These findings suggest that agreement between the cry signal and parent perception, also known as goodness of fit, optimizes development better than either a normal cry perceived as aversive or even an aversive cry perceived as not. Unfortunately, the logical presumption that how parents perceive cries determines parenting behavior has never been explicitly tested. Most research to date examines the relationship between parent perception and cry acoustics and/or contextual factors.

The second objective of cry assessment is to identify atypical cry signals that could interfere with the caretaking response. Table 7 shows the association between specific cry characteristics and cry perception. Overall, increases in f0 are most consistently associated with negative cry perception. Specifically, cries with higher fundamental frequency were rated as more aversive, sick, urgent, angry/sad, distressing, and arousing. Other cry characteristics that yield negative cry ratings include increased variability of f0, increased dysphonation, increased hyperphonation, increased duration, decreased voiced phonation ratio (VP ratio or the ratio between voiced sound to noise), and decreased amplitude.

The fidelity of cry perception is also affected by characteristics of the listener. Table 8 provides an overview of these characteristics known to have a significant impact on cry perception even with normal cry signals. Also included are measures of physiological response in the listener, which provide further evidence for the biological basis of the cry behavioral system operating in both infant and caregiver. Factors such as the age of the infant, the culture of the listener, maternal personality characteristics, maternal age, and maternal learned helplessness all have a significant impact on how the listener perceives/rates infant cry. Evidence for gender and parity effects is mixed, with some studies demonstrating significant and consistent effects, while others do not. However, the data do seem to suggest that parents are better at understanding the nature of cry, find it generally less aversive, and are more likely to provide caregiving than nonparents. Finally, factors such as depression, cocaine use, and teen motherhood not only appear to impact, but also to distort cry perception. These factors may be risk factors not only for misperception, but also for subsequent inappropriate provision of care.

**Table 7. Cry Characteristics That Affect Cry Perception**

| Type of Cry | Perception/Response | Studies |
|---|---|---|
| ↑ f0 | Rated as more aversive, sick, urgent, angry/sad, distressing, and arousing. | Adachi et al., [1985]; Okada et al., [1987]; Protopapas and Eimas, [1997]; Schuetze et al., [2003]; Schuetze and Zeskind, [2001]; Zeskind and Lester, [1978]; Zeskind and Marshall, [1988] |
| ↑ f0 variability | Rated as more urgent, sick, angry/sad, distressing, and arousing. | Protopapas and Eimas, [1997]; Zeskind and Marshall, [1988] |
| ↑ dysphonation | Rated as more intense, distressed, urgent, sick, aversive, grating, piercing, distressing, arousing, and discomforting. Reported shorter latency to caregiving. | Leger et al., [1996]; Gustafson and Green, [1989]; Wood and Gustafson, [2001] |
| ↑ hyperphonation | Rated as more aversive and sick. | Zeskind and Lester, [1978]; Zeskind and Marshall, [1988] |
| ↓ VP Ratio | Rated as more urgent, sick, grating, and arousing. | Adachi et al., [1985]; Okada et al., [1987] |
| ↑ duration | Rated as more urgent, sick, piercing, grating, aversive, distressing, arousing, and discomforting. | Cuisinier et al., [1998]; Gustafson and Green, [1989] |
| ↑ utterances | Rated as more distressed. Reported shorter latency to caregiving. | Wood and Gustafson, [2001] |
| ↓ amplitude | Rated as more urgent, sick, aversive, grating, piercing, arousing, and discomforting. | Gustafson and Green, [1989] |
| ↑ pauses between utterances/expiration | Rated as less informative, distressed, rough, abnormal, urgent, aversive, and arousing. Reported shorter latency to caregiving. | Wood and Gustafson, [2001]; Zeskind et al., [1992] |
| ↓ or ↑ expirations *and* shorter pauses | Rated as more urgent and sick. | Zeskind et al., [1992] |

It should be noted that cry perception studies employ different methodologies, including (1) the nature of the cry sample (e.g., hunger, pain, etc.), (2) natural cry samples versus cries generated or modified according to experimental specifications, and (3) the age of the infant (birth to 12 months). Nonetheless, cry perception studies show both the sensitivity of perception to atypical signals and also how vulnerable the interpretation of the signal is based on perceiver status. The misperception of the infant's signal could serve an adaptive function in some cases, for example, to reduce parental response to their infant based on their own emergency status. A parent and the infant would be well served if the parent assures her own survival before saving the infant, when both are under an acute threat. Psychiatric disorders in the perceiver (such as depression and anxiety disorders) may mimic parental emergency conditions and may alter parental response. But chronic parental hypo- or hyperresponsiveness to cry is not optimal to infant development and, in the case of extreme reactions to cry, may endanger the infant (e.g., shaken baby syndrome).

While testing parental cry perception is not part of routine medical care of the infant, clinicians should recognize parental concerns or lack of concern about crying that are inconsistent with the infant's cry behavior. The high prevalence of depression in young mothers raises the real possibility that the response of many mothers mismatches their infants' signals. While there are no structured tests available to identify misperception of infant cries, professionals in contact with parents and their infants during the early postpartum period can ask open-ended questions, such as "Tell me about the last month with your baby." Concerns about crying are typically part of parents' responses and open the door to discussion about understanding their infants' cry cues. The practitioner can follow up with more specific prompts, for example, "Any issues with crying?" or, during a crying bout, "What's going on with your baby?" Helping parents to correctly interpret their infants' cries can optimize development particularly in high risk infants who may have atypical signals or high risk parents who may misperceive a normal cry.

## CAUTIONS AND LIMITATIONS

Assessment of infant cry is a powerful screening tool to evaluate the neurological status of the newborn within its early biosocial context for physicians, nurses, early intervention specialists, occupational therapists, and other professionals that work with families during the postpartum period. However, there are several cautions to be considered. First, while atypical cry characteristics are sensitive to medical conditions and other prenatal insults such as drug exposure, cry measures do not display strong specificity. Therefore, like other screening tools, cry characteristics can overidentify poor prognoses. Second, although there is strong evidence that atypical cry characteristics reflect neurological insult, the implications for future development are not widely established. Third, different methodologies may yield different results. For example, the infant vocal tract has different characteristics than the adult vocal tract. Adult speech/sound analysis systems should be used with caution, particularly for F1 and F2.

## STRENGTHS/BENEFITS

Cry assessment is easy to administer and provides an early window into the neurological status of the infant. Atypical cries can be viewed as a positive screen that should be referred for a full neurological work up. Therapy with parents to understand their infants who show atypical cry characteristics can facilitate a positive developmental context during infancy and young childhood.

## FUTURE DIRECTIONS

The potential for cry assessment is largely untapped. The following initiatives include key technical, research, and clinical applications of acoustic cry analysis.

### Technical

- Develop a portable, easy to use cry collection device integrated with analysis software that utilizes algorithms for the infant vo-

**Table 8. Factors That Impact Cry Perception**

| Factors | Perception/Response | Studies |
|---|---|---|
| Age of infant | Cries of older infants were rated as more distressed and more intense. | Irwin, [2003]; Leger et al., [1996] |
| Cocaine user | Cocaine-using mothers rated cries as less arousing, aversive, urgent, and sick. They reported they would be less likely to pick up and feed the infant and more likely to give a pacifier or "wait and see." | Schuetze et al., [2003] |
| Contextual information | Listeners with contextual information (e.g., the baby needs sleep) reported longer latency to caregiving even despite distress ratings. | Wood and Gustafson, [2001] |
| Culture | Cuban-American and African-American mothers rated cries of at-risk infants as less aversive than than Caucasian mothers. Caucasian mothers were more likely to pick up and cuddle, Cuban-American mothers were more likely to give a pacifier, and African-American mothers were more likely to "wait and see." | Zeskind, [1983] |
| Depression | Depressed mothers showed ↓ sensitivity to changes in f0; rated ↑ f0 as less arousing and less salient, and were less likely to provide caregiving. | Donovan et al., [1998]; Schuetze and Zeskind, [2001] |
| Gender[a] | Men rated cries as more aversive, as eliciting more irritation and anger, and rated infants as more spoiled than women. Mothers rated cries as more likely to evoke sympathy and evoke caregiving than fathers. | Boukydis and Burgess, [1982]; Ziefman, [2003] |
| Maternal learned helplessness | Mothers in the learned helplessness condition showed dampened physiological and behavioral responses to subsequent crying. | Donovan, [1981]; Donovan et al., [1990] |
| Parental age | Younger parents were more likely to rate cry as aversive; however, teenage mothers of at-risk infants rated ↑ f0 as less aversive and a "better" cry, ↑ range of f0 as less piercing, and ↑ variability in and wider range of F1 as less piercing and less irritating. Older parents reported longer latency to caregiving. | Lester et al., [1989a]; Ziefman, [2003] |
| Parental personality/characteristics | Parents rated as more empathic, higher neuroticism, higher extraversion, and lower conscientious had more sensitive responses to infant distress. | Ziefman, [2003] |
| Parent vs. Non-parents | Mothers more accurately identified pain cries than non-mothers. Fathers more accurately identified hunger and pleasure cries than nonfathers. Parents rated cry as less aversive and distressed than nonparents. Parent ratings related to the overall cry pattern, while nonparent ratings were more related to discrete points within the cry. Mothers were more likely to provide caregiving in response to cry. | Green et al., [1987]; Irwin, [2003]; Wasz-Höckert et al., [1964]; Zeskind and Lester, [1978] |
| Parity[b] | Primiparous mothers were more likely to rate cry as a problem. Primiparous parents had higher skin potential levels and found cries of "average" infants to be the most arousing, whereas multiparous and nulliparous individuals fo und cries of "difficult" infants to be the most arousing. | Boukydis and Burgess, [1982]; Zeskind, [1980] |
| Colic[c] | Cries of infants with colic are rated as urgent, piercing, grating, arousing, and sad. | Lester et al., [1992] |
| Temperament[c] | Cries of "difficult" infants were rated as more irritating and angering, more spoiled, more likely due to psychological than physical causes, and were less likely to yield a caregiving response. | Boukydis and Burgess, [1982]; Lounsbury and Bates, [1982] |

[a]However, Green et al. [1987], Leger et al. [1996], and Zeskind et al. [1992] failed to find gender effects for cry perception.
[b]However, Adachi et al. [1985], Leger et al. [1996], Gustafson and Green [1989], and Okada et al. [1987] failed to find parity effects for cry perception.
[c]Colic and difficult temperament are associated with specific cry acoustics, which could account for cry perception.

cal tract and calculates outcome measures.

- Reduce the number of variables to a meaningful set of outcome measures to be integrated in the data collection system, including a profile of the infant, norms, and clinical cutoffs for ease of interpretation.
- Develop structured interviews or brief tests that evaluate parent perception of normal and abnormal cries.

### Research

- Conduct research to establish clinical cutoffs, profiles, or norm-based reference databases to assist in interpretation of cry characteristics.
- Conduct long-term studies of neurologically involved and at-risk infants to determine if infants with atypical cries have the poorest prognosis.
- Conduct research to establish the relationship between parent perception and parent behavior.
- Include nonpain cries along with pain cries in future research of potential nervous system insult. The concern for the effect of disrupted signals by high risk infants on parent perception and caretaking response is not fully tested by pain cries as most of the cries parents encounter are nonpain cries.

### Clinical Applications

- Train residents or other health professional how to "listen" and evaluate abnormal cries.
- Educate parents on the language of cry. Parents can monitor their infant's cries and report to the infant's physicians any changes that may indicate unusual distress or potential medical problems.
- Include assessment of cry perception in high risk mothers or with high risk infants in primary care, early intervention, and occupational therapy. ■

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