Chapter

The Frequency Following Response: Evaluations in Different Age Groups

Milaine Dominici Sanfins, Michele Vargas Garcia, Eliara Pinto Vieira Biaggio and Piotr Henryk Skarzynski

Abstract

In this chapter, recent data on the clinical application of the frequency following response (FFR) in different age groups will be presented. The chapter begins with the importance of using speech sounds in electrophysiological assessments. Then the FFR methodology is presented, giving normative data and the expected responses in different age groups: infants and young children, children and adolescents, and adults and the elderly. Finally, the unique responses of each age group are presented in order to show how this new technology can be an extremely useful tool for diagnosing hearing dysfunction.

Keywords: electrophysiology, frequency following response, speech perception, hearing, auditory evoked potential

1. Introduction

Until recently, electrophysiological evaluations were performed exclusively with nonverbal stimuli such as clicks and tone bursts which allow rapid and synchronous stimulation of neurons. However, the use of verbal stimuli, such as speech sounds, allows a more accurate analysis of the auditory system, especially if the aim is to investigate how the system decodes speech sounds involved in daily communication. Verbal and nonverbal stimuli are decoded in different ways and follow different trajectories through the central auditory nervous system.

Human communication consists predominantly of verbal stimuli, and it is important to understand how verbal sounds are coded at various levels of the auditory system. The need to develop research methods that are objective and accurately represent daily listening led to the development early this century of electrophysiological tests for measuring how speech sounds are perceived [1, 2]. Subsequently, a number of research groups have focused their efforts on using complex stimuli such as speech for diagnostic purposes [3–10].

The initial studies were performed in animal models [11] aiming to evaluate how the temporal and spectral properties of verbal stimuli were coded, and later human responses were also analyzed [12]. Among the electrophysiological procedures for investigating the processing and coding of verbal sounds, we highlight the frequency following response (FFR).

2. Frequency following response

Acquisition of an FFR is very similar to collecting an ABR with a click stimulus. However, interpretation of an FFR requires that the audiologist has a more sophisticated knowledge base. Speech stimuli allow a more complex analysis of the responses, such as their:

- timing;
- magnitude;
- frequency content and magnitude;
- frequency tracking;
- phase consistency;
- intrinsic factors; and
- difference between individual responses.

An FFR evaluation can be performed on different clinical populations and age groups, and below we give details of how the procedure varies depending on the patient's age. Because FFR is a relatively new procedure, initial work was done on adult subjects. Afterward, researchers turned their interest to the study of responses in infants and young children, children and adolescents, and the elderly.

In order for an FFR assessment to be useful in identifying auditory disorders at an early stage, normative values using different equipment and recording parameters need to be established and compared with language acquisition markers.

The distinctive features of FFRs in different age groups will be presented in three parts:

- evaluation in infants;
- evaluation in children and adolescents;
- evaluation in adults and the elderly.

3. Frequency following response: evaluation in infants

In clinical practice, a comprehensive hearing evaluation for infants and young children is essential, since the integrity of their auditory system is the basis for acquiring oral language. In this context, if one measures only the functioning of the peripheral auditory pathway, perhaps by recording and analyzing otoacoustic emissions and/or auditory brainstem evoked potentials, it significantly constrains one's knowledge of the patient's hearing status. Moreover, behavioral assessments of hearing in very young children are often inconclusive, considering the diversity of neuropsychomotor development in this age group.

The perception of speech is important for the development of receptive and expressive language [13]. Through auditory experiences, infants and toddlers acquire and master the linguistic elements necessary for effective communication. The experiences are associated with information from the other senses, and together

they allow the acquisition and development of oral language. Through listening, the subject understands oral language and creates concepts, finally inter-relating them and expressing them through speech [14]. Thus, the importance of hearing for the acquisition and development of language is vital, and any disturbance to the auditory pathway has implications for oral communication as a whole [14].

FFR testing can be used with infants and young children as a predictor of the extent of future language appropriation—in other words as a way of identifying children who are at risk of deficits in oral language acquisition [2, 15]. Assessment by FFR of infants and young children is relatively recent, and published studies of its potential have only been done over the last decade. Before discussing what is known about FFR in this population, it is first necessary to clarify an important factor: maturation of the auditory pathway.

It is known that peripheral hearing is functional even before birth, whereas myelination and the organization of neural connections keep developing after birth [16, 17]. Indeed, the central structures, such as the subcortex and cortex, develop throughout the early years of human life. There is an ascending myelination of the auditory pathway, evidenced by magnetic resonance imaging. Up to the 13th week of life, there is an increase in myelination density of the cochlear nucleus, the superior olivary complex, and the lateral lemniscus, with the inferior colliculus demonstrating an increase in density around the 39th week of life [18]. This continuous process of myelination of the higher structures of the auditory pathway during the first year of life must be considered when evaluating the FFR, for it means that the lower the age of the evaluated subject, the greater the latency of the FFR waves [19, 20]. This increase in latency can also be seen in other auditory evoked potentials [21]. An FFR can be recorded from a neonate, but the responses only become readily apparent from the third month of age [15]. The existence of a series of FFR waves—V, A, C, D, E, F, and O—in neonates has been pointed out by several researchers [15, 19, 22–26]. FFR evaluations have been performed with the vowel /i/ [15, 24], the syllables /ba/ and /ga/ [26], and the syllable /da/ [23].

The FFR has been studied in neonates of different nationalities (Chinese, American) during the first days after birth, and the FFRs were nearly the same. This finding makes it possible to infer that, independent of the mother tongue, there is an innate capacity for speech coding in neonates at the subcortical level [22].

The evaluation of subcortical representation of speech coding was studied by evaluating FFRs in 28 healthy North American infants, 3–10 months of age. The study focused on the fundamental frequency (F0), the response time of the FFR, and the representation of harmonics. To analyze the data in the frequency domain, spectral amplitudes were calculated by fast Fourier transform (FFT) and divided into three frequency ranges: F0, 103–125 Hz; first formant (F1), 220–720 Hz; and high harmonics (HH), 720–1120 Hz. The F0 responses were more robust in infants 3 months of age and the amplitude of F0 did not show significant changes over the entire 6 months. For the F1 and HH frequencies, there was a rapid and systematic increase of amplitude from 3 to 6 months of age.

To analyze the data in the time domain, the peaks were identified manually and confirmed by a second observer. Waves I, III, and V were first identified in response to a click, and then, in the FFR, the same peak and following valley (V and A), the peaks (D, E, and F), and the displacement peak (O). Non-detectable peaks were marked as missing data points and were excluded from analysis. The latencies and amplitudes (baseline to peak) were extracted from the identified waves. The time domain analysis demonstrated a decrease in neural conduction time and an improvement in amplitude with increasing age. The latencies of A and O, the time interval between A and O, and the slope between V and A were shown to have a negative correlation between latency and age. In addition, there was an improvement in the morphology

of all waves as age increased. It was also observed that infants 3–5 months of age had longer latencies, smaller intervals between A and O, and a lower V/A slope compared to those 6–10 months of age. This negative correlation between the latencies and the age of the infants, as well as the decrease of slope in the smaller children, is due to a maturational process occurring in the subcortical auditory system and shows that there is less neural synchrony in younger infants [23]. The authors also note that these findings indicate that at approximately 6 months of age, the coding of speech characteristics, both spectrally and temporally, becomes more like those of an adult, although the changes continue through to school age. These findings indicate that FFR evaluation can detect early disorders in the perception of speech sounds.

The researchers also investigated the development of subcortical speech processing in Chinese infants born in households in which the mother tongue was Mandarin. They recorded FFRs at two ages: 1–3 days of life and at 3 months. This prospective-longitudinal design study included only infants who had undergone auditory screening at birth, who had no obvious neurological disorders, and did not have any risk indicator for hearing loss. Initially, 44 newborns were tested by FFR during natural sleep. After that, the sample was divided into groups. For each group, the researchers selected different speech stimuli for the evaluation of FFR (monosyllables contrasting with Mandarin). Only 13 infants completed the follow-up protocol at the third month. The processing and tracking of the fundamental frequencies of human speech at the subcortical level, evidenced by the FFR, showed more robust responses when the babies were 3 months old. Researchers acknowledged the limitations of the study, including statistical analysis and data interpretation. A research weakness was the relatively low completion rate (i.e., 17/44 infants or 38.64%). This factor undermined the power of the conclusions and prevented the possibility of performing statistical analyses for each Mandarin tone used. Despite the limitations of the study, the findings fill a gap in understanding the developmental trajectory of subcortical processing during the first 3 months of life [25].

From the theoretical assumptions highlighted in the previous reference, it should be noted that the linguistic environment of a newborn has a substantial effect on the development of its speech perception. Even at birth, children are able to detect subtle differences in verbal sounds. Newborns can effectively differentiate all the features of human speech and most infants who participated in an FFR follow-up showed improvement in pitch tracking and response amplitudes at 3 months of age [25]. Such neural refinements observed by FFR are often highlighted in the literature for both infants [22, 24] and young infants [15, 23]. For example, in a longitudinal case report of one infant, the researchers obtained FFR records when the infant was 1, 3, 5, 7, and 10 months old. The results showed an evolving trajectory of development with a transition point of about 3 months [15].

Using FFR evaluation in preterm infants may also be an alternative for the early diagnosis of auditory disorders in this population related to the perception of speech sounds. Premature babies are at high risk of developing language disorders, so using FFR may be a way of measuring immature neural activity and predicting possible changes in the processing of verbal sounds. In order to do so, one study evaluated 12 premature Indian infants through FFR with the aim of exploring how an immature auditory system responds to complex acoustic stimuli such as speech [27]. Peaks V, A, C, D, E, and F were detected in almost all babies and with latencies and amplitudes similar to those reported in the literature. The waves could be replicated. The authors conclude that FFR may be a way of understanding how the human brain-stem receives speech signals and that such an assessment might be important for all high-risk babies. Although the findings of this study cannot be generalized, mainly due to the limited data (small sample and absence of a controls, among others), they point out the potential of FFR in evaluating infants from neonatal intensive care units.

More recently, studies that record FFRs in the presence of background noise have been published. It is known that competing noise can make speech comprehension more difficult in people of all ages. Speech-in-noise tests are clinically available but cannot be given to infants. Thus, the use of FFRs in noise may be an alternative for evaluating impaired speech perception in young children who are unable to respond to behavioral tests.

In this context, with the objective of examining the electrophysiological responses in the presence of noise, researchers have evaluated the FFR in 30 children with typical development under conditions with and without noise (a signal-to-noise ratio of +10 dB in the former) [28]. Babies were divided into two age groups: 7–12 and 18–24 months. For all infants, frequency analysis of the FFR with a Fourier transform was performed, analyzing the latency and amplitude of waves V, A, D, E, and F, and correlation tests were carried out. In both groups, the mean latency of all recorded waves was higher in the presence of noise. According to the authors, this suggests that, at least for infants up to 24 months, the presence of noise causes a delay in the appearance of FFR waves independent of age. In addition, they observed a greater amplitude of F0 in the noise condition in the group of older babies; this difference was not seen in the silent condition. Thus, the authors point out that, at 2 years of age, infants are less vulnerable to the degrading effects of noise compared to children younger than 12 months.

The development of phase lock and frequency representation has also been evaluated in infants. This was the focus of a study that included an initial sample of 56 typical babies, aged between 2 and 12 months, and evaluated the FFR with /ba/ and /ga/ stimuli presented in the right ear using the SmartEP equipment from Intelligent Hearing Systems [26]. These responses were also obtained in young adults to provide a reference for the course of development of neural synchrony (represented by phase lock) and response amplitude (represented by spectral magnitude). The results obtained in this study demonstrate that the strength of phase-lock in the fine structure at CV transition is higher in young adults compared to infants. However, phase lock for F0 was equivalent between adults and infants. The frequency of F0 was found to be higher in older infants compared to younger infants and adults. Thus, these data demonstrate that speech coding can be evaluated in infants from 2 months of age and that such data are of value in a clinical setting, since it is known that performing electrophysiological evaluation of hearing in young children is difficult because they are less able to remain still during a test. The data indicate that the FFR may be a way of testing babies who are at risk of developing a language disorder, examining the auditory coding mainly of the midbrain, but also reflecting contributions from the auditory nerve, brain stem, and cortex.

The most commonly used parameters in FFR evaluations are: monoaural stimulus, right ear stimulation, intensity of 80 dB SPL, syllable /da/ speech stimulus, alternating polarity, presentation rate of 10.9 stimuli per second, vertical placement of electrodes, insert headphones, and the subject sitting distracted or awake during recording [29].

Regarding the latency parameters, when FFR is done with the Navigator Pro AEP System (Natus Medical, Inc.) and a syllable stimulus, one group of researchers [19] pointed out that in 23 normal-hearing babies (0–12 months) the wave latencies were on average: V = 7.22 ms, A = 8.22 ms, D = 23.14 ms, E = 31.5 ms, F = 39.91 ms, and O = 49.64 ms. FFR wave latencies were also investigated in 53 children aged 3–5 years (**Tables 1** and **2**).

Parameters of FFR evaluation in infants and young children used in the Hearing Electrophysiology Service of the Federal University of Santa Maria, Brazil, are presented in **Table 3**.

	Waves					
	V	A	D	E	F	O
	Lat	Lat	Lat	Lat	Lat	Lat
∑	7.22	8.22	23.14	31.51	39.91	49.64
SD	0.42	0.43	0.66	0.49	0.45	1.32
Detect (%)	86.9	86.96	91.30	91.30	82.61	65.22

∑: average (ms), SD: standard deviation, Detect: the percent detectability for each peak.
Sample: 23 babies (0–1 years old).

Table 1.
FFR latency values using syllable /da/of 40-ms duration performed on babies with normal hearing (silent background) [19].

	Waves					
	V	A	D	E	F	O
	Lat	Lat	Lat	Lat	Lat	Lat
∑	6.59	7.56	22.36	30.90	39.34	48.14
SD	0.26	0.35	0.38	0.37	0.32	0.42
Detect	100	100	88.67	98.11	100	90.57

∑: average (ms), SD: standard deviation, Detect: the percent detectability for each peak.
Sample: 53 children (3–5 years old).

Table 2.
FFR latency values using syllable /da/ of 40-ms duration performed in children with normal hearing (in silence) [19].

Presentation parameters	Setting
Equipment	SmartEP, Intelligent Hearing Systems (IHS)
Transducer	Insert phones
Electrodes	Fz; Fpz; M1; M2 or Cz, M1, M2
Stimulation	Right ear
Stimulus	Syllable /da/
Duration of stimulus	40 ms
Presentation rate	10.9/s
Window	80–100 ms
Filter	Low pass of 100 Hz and high pass of 2000 Hz Low pass of 100 Hz and high pass of 3000 Hz
Polarity	Alternating
Intensity	80 dBnHL
Number of stimuli	6000
Reproducibility	2 × 3000 stimuli
Condition of evaluation	Awake and quiet
Impedance	3k Ohms
Artifact rejection	Acceptance if <10%

ms, millisecond; s, second; Hz, hertz; dB, decibel; HL, hearing level.

Table 3.
Parameters of FFR in infants and young children.

Source	Latency (ms)		Amplitude (μV)		VA measures	
	Σ	SD	Σ	SD	Σ	SD
V	6.61	0.25	0.31	0.15		
A	7.51	0.34	0.65	0.19		
C	17.69	0.48	0.36	0.09		
F	39.73	0.61	0.43	0.19		
Slope VA (μV/ms)					0.13	0.05
Area VA (μV × ms)					1.70	1.23

∑: average, SD: standard deviation.
Sample: 36 and 38 children and adolescents (8–12 years old) with normal hearing.

Table 4.
FFR latency and amplitude values using the syllable/da/of 40-ms duration, performed in children with normal hearing on the right ear (silent conditions) [12].

		Waves													
		V		A		C		D		E		F		O	
	Sex	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp
Σ	M	6.53	0.10	7.53	0.19	18.43	0.08	22.29	0.17	30.86	0.21	39.31	0.17	48.02	0.13
	F	6.49	0.13	7.43	0.23	18.33	0.12	22.28	0.15	30.81	0.29	39.27	0.24	47.95	0.21
Med	M	6.49	0.10	7.53	0.18	18.28	0.07	22.24	0.09	30.86	0.21	39.28	0.7	48.11	0.13
	F	6.49	0.12	7.37	0.22	18.37	0.09	22.11	0.13	30.78	0.22	39.11	0.24	47.86	0.21
SD	M	0.19	0.05	0.32	0.04	0.44	0.05	0.32	0.07	0.53	0.07	0.44	0.08	0.45	0.07
	F	0.22	0.07	0.35	0.90	0.44	0.11	0.67	0.09	0.58	0.35	0.56	0.26	0.75	0.28

∑: average, Med: median, SD: standard deviation, M: male, F: female.
Sample: 40 children and adolescents (8–16 years old).

Table 5.
FFR latency and amplitude values for males and females using syllable /da/ of 40-ms duration performed in children with normal hearing (silent conditions) [30].

		Complex VA	
	Sex	Slope VA (ms/μV)	Area VA (ms × μV)
∑	M	0.31	0.29
	F	0.39	0.34
Med	M	0.29	0.31
	F	0.36	0.31
SD	M	0.11	0.09
	F	0.14	0.14

∑: average, Med: median, SD: standard deviation, M: male, F: female.
Sample: 40 children and adolescents (8–16 years old).

Table 6.
Complex VA (slope and area) values for males and females using syllable/da/of 40-ms duration performed in children with normal hearing (silent conditions) [30].

The early identification of hearing disorders through FFR evaluation allows a speech-language pathologist to intervene, lessening the damage that this disorder can have on the development of speech skills in early childhood [2, 20, 22, 31]. This

		Waves													
		V		A		C		D		E		F		O	
	Ear	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp
Σ	R	6.50	0.12	7.46	0.22	18.33	0.10	22.21	0.14	30.89	0.30	39.37	0.24	48.00	0.21
	L	6.51	0.11	7.48	0.21	18.41	0.11	22.36	0.13	30.78	0.23	39.20	0.19	47.95	0.16
Med	R	6.45	0.12	7.45	0.21	18.33	0.08	22.12	0.14	30.86	0.23	39.24	0.19	47.99	0.15
	L	6.53	0.11	7.41	0.21	18.33	0.09	22.28	0.11	30.78	0.21	39.07	0.18	48.03	0.15
SD	R	0.21	0.06	0.33	0.09	0.42	0.08	0.66	0.09	0.50	0.39	0.55	0.29	0.75	0.30
	L	0.21	0.06	0.36	0.07	0.46	0.10	0.44	0.08	0.61	0.09	0.47	0.09	0.54	0.12

Σ: average, Med: median, SD: standard deviation, R: right, L: left.
Sample: 40 children and adolescents (8–16 years old).

Table 7.
FFR latency and amplitude values for right and left ears using syllable/da/of 40-ms duration performed on children with normal hearing (silent conditions) [30].

	Complex VA		
	Ear	Slope VA (ms/μV)	Area VA (ms × μV)
Σ	R	0.37	0.33
	L	0.34	0.31
Med	R	0.32	0.31
	L	0.32	0.31
SD	R	0.14	0.13
	L	0.13	0.13

Σ: average, Med: median, SD: standard deviation, R: right, L: left.
Sample: 40 children and adolescents (8–16 years old).

Table 8.
Complex VA (slope and area) values for right and left ears using syllable/da/of 40 ms duration performed on children with normal hearing (silent conditions) [30].

		Waves													
		V		A		C		D		E		F		O	
	Age range	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp	Lat	Amp
Σ	8–11	6.53	0.12	7.44	0.22	18.37	0.11	22.26	0.15	30.80	0.25	39.34	0.21	47.95	0.17
	12–16	6.46	0.11	7.51	0.21	18.36	0.10	22.32	0.10	30.89	0.28	39.19	0.21	48.02	0.21
Med	8–11	6.53	0.11	7.45	0.21	18.37	0.09	22.20	0.14	30.78	0.23	39.28	0.20	47.95	0.15
	12–16	6.45	0.12	7.45	0.17	18.28	0.08	22.20	0.09	30.86	0.20	39.11	0.15	48.03	0.13
SD	8–11	0.23	0.06	0.32	0.10	0.46	0.09	0.53	0.08	0.62	0.19	0.56	0.11	0.75	0.14
	12–16	0.17	0.06	0.37	0.07	0.41	0.08	0.63	0.45	0.43	0.22	0.42	0.32	0.46	0.33

Σ: average, Med: median, SD: standard deviation, R: right, L: left.
Sample: 40 children and adolescents (8–16 years old).

Table 9.
FFR latency and amplitude values for various age ranges using syllable/da/of 40-ms duration performed on children with normal hearing (silent conditions) [30].

assertion can be understood by appreciating the relationship between language development and the presence of stimulating auditory experiences in the first few months of life.

Future studies evaluating FFRs in infants will no doubt benefit from interdisciplinary collaboration which seeks to deepen understanding of the underlying mechanisms involved in the typical and atypical development of the auditory system during early childhood.

4. Frequency following response: evaluation in children and adolescents

Auditory impairment is almost invariably associated with language and communication deficits. Learning a spoken language depends on assimilating the acoustic and phonetic elements of a language [32]. The development of the central auditory nervous system begins in intrauterine life and continues until adolescence, over which time hearing abilities become more complex and elaborate.

Because of the close relationship between hearing, language, and learning, it is extremely important to monitor hearing over the course of life. Especially in children, be it pre-school or school age, the aim should be to monitor auditory function, either through behavioral or electrophysiological assessments. The ideal would be a combination of both behavioral and electrophysiological methods, so that with numerous evaluations there are crosschecks which allow a more accurate diagnosis to be made.

The electrophysiological procedure traditionally used in clinical practice is the click ABR. However, in evaluating children with language deficits, this type of sound stimulus is not ideal for making diagnoses. Assessments using verbal sound stimuli, such as used in FFR, appear to be more effective and reliable in cases of learning problems or school difficulties [6]. Evaluation via an FFR allows a detailed analysis of how verbal stimuli are encoded in the central auditory nervous system to be done.

The FFR allows fine-grained auditory processing deficits associated with real-world communication skills to be identified. As well as being used for the early identification of auditory processing, it can also be used to assess hearing across different clinical populations [33, 34]. This electrophysiological procedure can provide reliable and objective information about acoustic patterns such as timing, pitch, and timbre [35]. These three elements can be evaluated using different parts of the FFR, as follows:

- timing—via analysis of the onset and offset portions;
- pitch—by analysis of the fundamental frequency (F_0);
- timbre—from analysis of the harmonics of F_0.

Simplistically, it can be said that the FFR helps in understanding which speech sounds were spoken (their timing and harmonic cues) and who said it (pitch cues) [36]. In addition, an FFR test can be performed under two conditions: (i) in silence (presentation of verbal stimuli only), and (ii) in noise (presentation of verbal stimuli plus background noise).

In children and adolescents, studies have shown that FFRs change in latency as age increases. FFRs of children aged around 5 years appear to be very similar to the responses of children aged 8–12. However, the FFR pattern of children under 5 years has a somewhat different morphology and latency. According to Johnson et al. [33], the differences in children younger than 3 years are more evident in the initial portion of the responses (the onset), while in older children the change is more evident in the final portion (the offset) [3, 37].

Initial studies have focused on understanding the FFRs in children and adolescents under silent conditions and in subjects who have normal hearing and typical development. For the benefit of clinical audiologists, some of these studies are summarized below (**Tables 4–9**).

Table 10 shows the parameters used in children and adolescents at the Electrophysiology Department of the State University of Campinas using Biologic equipment and BioMARK software.

Because FFR is a new procedure, unstudied pathologies are gradually being added and, little by little, we are gaining new information about what effects the pathologies have on the responses of affected children and adolescents.

The FFRs of children diagnosed as poor readers frequently present as alterations in the timing and magnitude of timbre components [38]. The perception of the duration of a sound stimulus is essential for proficient reading, and the FFR can evaluate or monitor a decline in temporal and spectral precision. Children and adolescents with dyslexia commonly have difficulty perceiving speech sounds either in silence or in competing noise backgrounds. If a child has difficulty in perceiving speech sounds, their reading can be severely impaired [39]. Recently, Sanfins et al. [6] highlighted the importance of FFR as a biological marker in scholastic difficulties.

FFR evaluation in children who have suffered from secretory otitis media in the first 6 years of life, and who have undergone myringotomy for bilateral ventilation tube placement, exhibit changes in their FFR compared to normal children [5]. This study found that evaluating the FFR seems to be a promising method of identifying

Parameter	Settings
Equipment	Biologic Navigator Pro
Software	BioMARK
Electrode montage	Cz, M1, and M2
Stimulated ear	Right ear
Stimulus	Speech
Stimulus type	Syllable /da/
Stimulus duration	40 ms
Stimulus polarity	Alternating
Stimulus intensity	80 dB SPL
Stimulus rate	10.9/s
Number of sweeps	6000
Replicability	Twice for 3000 sweeps
Transducer	Insert
Assessment condition	Watching a movie
Impedance	1k Ohms
Window 85.33 ms	85.33 ms
Filter	100–2000 Hz
Artifact rejection	>10%

Cz: vertex, M1: left mastoid, M2: right mastoid, ms: millisecond, dB: decibel, SPL: sound pressure level, s: second, Hz: hertz.

Table 10.
Parameters of FFR in children and adolescents.

changes in the coding of speech stimuli in these children which might be undetected using traditional electrophysiological evaluation. The changes in their electrophysiological responses might serve as an alert to parents and educators, who can then adopt strategies to minimize the negative consequences on language development and academic achievement.

Another possibility for using FFR assessment may be in monitoring an auditory training program or even tracking the effect of therapeutic interventions. Studies have shown that children with learning disabilities can benefit from an auditory remediation program, and it might therefore be usefully accompanied by FFR examinations (because FFRs have good repeatability in test and retest) [40, 41]. In addition, bilingual children can also be monitored through FFR assessment. Researchers have confirmed that neural perception of speech seems to be more consistent in bilinguals than in monolinguals [42, 43]. Bilingual experience during childhood may favor plasticity in the neuronal coding of sound and improve fundamental frequency perception (F0).

Recently, the neurophysiological aspects of speech perception have been investigated in cases of autism spectrum disorder (ASD). The results showed that children with ASD tend to have changes in the sensation of pitch (frequency), which might explain a withdrawal from speech reception. The fundamental frequency (F0) and its harmonics contain speech information which is essential in conveying affect [44], so changes in FFRs are consistent with a defect in perceiving prosody. The inference is that prosody deficits in some ASD patients may derive from an inability to encode and transmit auditory information in the brainstem [45].

Traditionally, FFR testing is done by presenting verbal stimuli through an insert earphone with a silent background. However, the perception of speech in a noisy background is a much discussed topic. In the presence of noise, normally hearing individuals need to make constant adjustments in their central auditory nervous system to satisfactorily understand and process speech information. Of course, there are others who, in the presence of competing noise, experience great difficulty in understanding speech [46].

The evaluation of FFR in the presence of noise can be effectively used to diagnose children with learning disabilities [47]. Thus, identification of such children could lead to improvements in their reading and writing skills and in daily communication.

5. Frequency following response: evaluation in adults and the elderly

In the adult and elderly population, the need for detailed audiological investigation increases when the patient complains of hearing difficulties, even if auditory thresholds appear normal.

The evaluation of the FFR first involves time and prosody recordings, which provide important information about consonant and vowel discrimination and also aid in the perception of intonation [48]. For adults, but especially in the elderly, participation in these sorts of tests can assist in rehabilitation, either using a hearing aid or auditory training (or both).

The clinical usefulness of the FFR in gauging how well auditory information is being processed is unquestionable. In adults and the elderly, many studies have already been done to identify how the FFR can help in diagnosing complaints related to central auditory processing, thereby allowing better rehabilitation.

The latencies (mean and standard deviation) for adults and the elderly are presented in **Table 11**. The values come from Skoe et al. [19] who used Biologic and

	Complex VA		
	Age range	**Slope VA (ms/μV)**	**Area VA (ms × μV)**
∑	8–11	0.38	0.31
	12–16	0.33	0.34
Med	8–11	0.37	0.31
	12–16	0.28	0.31
SD	8–11	0.12	0.11
	12–16	0.16	0.16

∑: average, Med: median, SD: standard deviation, R: right, L: left.
Sample: 40 children and adolescents (8–16 years old).

Table 11.
Complex VA (slope and area) values for age range using syllable/da/of 40-ms duration performed in children with normal hearing (silent conditions) [30].

Age (years)	**Number**	**Latencies (maximum in milliseconds + 2 SD)**					
		V	**A**	**D**	**E**	**F**	**O**
17–21	54	7.04	8.15	23.21	31.9	39.50	48.94
21–30	143	7.17	8.28	23.4	32.54	40.84	49.79
30–40	32	7.27	8.39	23.64	32.09	40.38	49.13
40–50	11	7.05	8.22	24.26	31.86	39.93	49.6
50–60	26	7.5	8.77	24.5	32.97	41.46	50.72
60–73	24	7.68	8.81	24.27	32.47	40.60	50.02

Data from [19].
SD: standard deviation.

Table 12.
*FFR latency values based on mean values in **Table 11** plus two standard deviations.*

Navigator Pro equipment. In this study, subjects aged between 18 and 72 years and distributed in 6 age brackets were used. In the case of adults, the authors list values for subjects aged 21–30 years (n = 143) and found that latency values tended to increase with age. Thus, the researchers emphasized the importance of conducting research on FFRs in different age groups, since normative values can be modified with the aging process.

In **Table 12** the maximum values of each wave are listed by adding two standard deviations to those in **Table 13**. Assuming the distribution is Gaussian means that this measure will cover 95% of the population.

Undoubtedly, the largest number of FFR studies have been performed using the Navigator Pro model from Biologic. Researchers tend to use this equipment together with the Intelligent Hearing Systems and SmartEP software [7, 49, 50].

One study aimed to assess the processing of auditory information in those with hearing loss through an evaluation of eight individuals, aged 46–58 years, with hearing loss [7]. FFRs (collected by SmartEP) were correlated with results from two auditory processing behavioral tests—the masking level difference test and the random gap detection test. No correlation was found between FFR and these tests. The researchers found that the generation of this potential is extremely complex and could encompass several functions and does not depend on just temporal resolution

Age	Number	Latency ∑ (mean in milliseconds)						Standard deviation											
		V	A	D	E	F	O	V (SD)	%	A (SD)	%	D (SD)	%	E (SD)	%	F (SD)	%	O (SD)	%
117–21	54	6.58	7.53	22.41	31.02	39.50	48.26	0.23	100	0.31	96.30	0.40	92.6	0.44	94.44	0.46	98.15	0.34	98.15
221–30	143	6.65	7.60	22.60	31.12	39.61	48.33	0.26	100	0.34	100	0.67	95.8	0.71	100	0.62	99.30	0.73	97.90
330–40	32	6.61	7.53	22.52	31.09	39.54	48.21	0.33	100	0.43	100	0.56	96.88	0.50	96.88	0.42	96.88	0.46	93.75
440–50	11	6.67	7.64	22.84	31.26	39.49	48.30	0.19	100	0.29	100	0.71	90.90	0.30	100	0.22	100	0.65	90.90
550–60	26	6.86	7.89	23.08	31.57	39.92	48.72	0.32	92.31	0.44	92.31	0.71	76.92	0.70	96.15	0.77	92.31	1.00	88.46
660–73	24	6.92	7.89	23.05	31.37	39.68	48.84	0.38	91.67	0.46	91.67	0.61	83.33	0.55	83.33	0.46	83.33	0.59	100

∑: Average (ms), SD: standard deviation, %: percent detectability for each peak.

Table 13.
FFR latency values for syllable /da/ of 40-ms duration, (silence) performed in adults and the elderly with normal hearing [19].

or selective attention [7]. Also seeking to correlate FFRs with hearing loss, Peixe et al. [49] evaluated 11 individuals, aged 23–59 years, with moderately severe hearing loss. They concluded that hearing loss may cause an increase in the FFR wave latency, but the waves are still present so long as the stimulus intensity is adjusted. In other words, the presence of FFR waves is related to the audibility of the signal.

Another interesting study was conducted with 30 young Indian adults aged 18–25 years [50]. The evaluation was carried out with the SmartEP equipment, and FFRs were present in all subjects evaluated. The latency and amplitude values of the analyzed elements were: wave V (lat = 6.81 ms and amp = 0.19 μV), wave C (lat = 16.82 ms and amp = 0.24 μV), wave D (lat = 24.75 ms and amp = 0.32 μV), wave E (lat = 31.36 ms and amp = 0.37 μV), and wave F (lat = 40.04 ms and amp = 0.29 μV).

Worldwide, there is a large increase in the number of elderly people. This entails providing better care for the elderly in all aspects of their health. With aging, there are structural changes in the peripheral and central auditory system which can lead to a decline in hearing. This, in turn, causes complaints of difficulty in understanding speech, especially in unfavorable environments [51, 52]. These impairments have a great impact on the life of the elderly, since in addition to causing social isolation, it can also lead to a depression and reduce cognitive function [53].

Only a few studies have focused on FFR in the elderly, with the most reported population being young adults [54]. Some researchers have pointed to the clinical applicability of FFR in different populations and with different pathologies [7, 19, 37, 55].

The effects of presbycusis on FFRs have been investigated in 18 individuals aged 61–78 years with hearing loss at frequencies of 2, 4, and 8 kHz (and compared with the responses of a control group of 19 young adults aged 20–26 years with normal hearing) [37]. The elderly group had lower amplitudes and increased latencies compared to the control group, demonstrating that the FFR can be affected by aging as well as hearing loss, but in different ways.

The effects of hearing loss on FFRs were described in a sample of 30 elderly individuals aged 60–71 years who were divided into two groups matched by gender and intelligence quotient: (i) normal hearing, and (ii) mild to moderate hearing loss [35]. With ABR clicks, all subjects had normal responses. FFR testing indicated that individuals with hearing loss could be assessed with this procedure, but there were changes in the frequency responses. In the elderly with hearing loss, there was a breakdown in the perception of the speech signal, which resulted in differences in signal parameters compared to the group with normal thresholds. This breakdown in neural synchrony may explain the greater difficulty subjects with hearing loss have in speech perception.

The evaluation of FFR in noisy environments is becoming more widespread, Thus, one study was carried out with 111 individuals between 45 and 78 years of age (mean 61.1 years) with normal to moderate hearing loss [56]. All subjects presented values within normal limits for the Montreal Cognitive Assessment (MoCA) and click ABR. In addition, they were tested on the SSQ (Speech, Spatial, and Qualities of Hearing Scale) which relates to auditory quality, as well as to the Quick Speech-in-Noise test (QuickSIN), in which phrases are presented binaurally with a verbal background babble. The FFR assessment demonstrated an increase in O-wave latency associated with speech comprehension difficulty in competing noise environments.

Supporting the observation that FFR traces are affected by increasing age, research on 34 individuals aged 22–77 years with normal hearing [57] found a decrease of the amplitude was associated with an increase in latency (**Figures 1** and **2**).

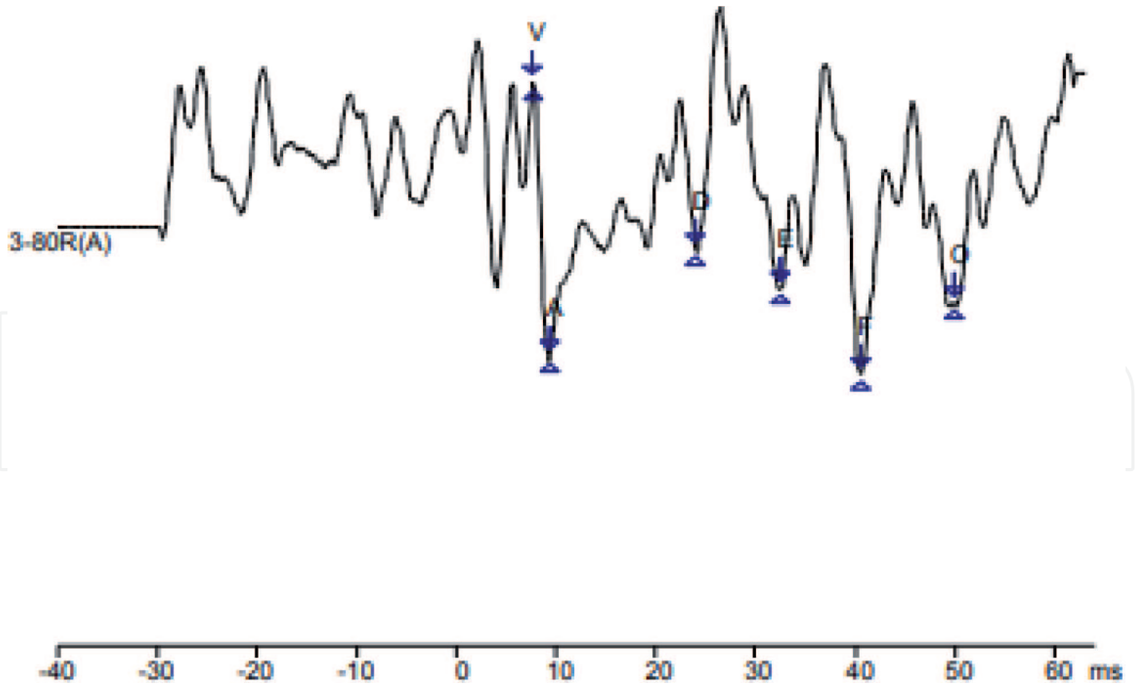

Figure 1.
FFRs of an infant 13 days old. Authors' data with FFR performed using SmartEP.

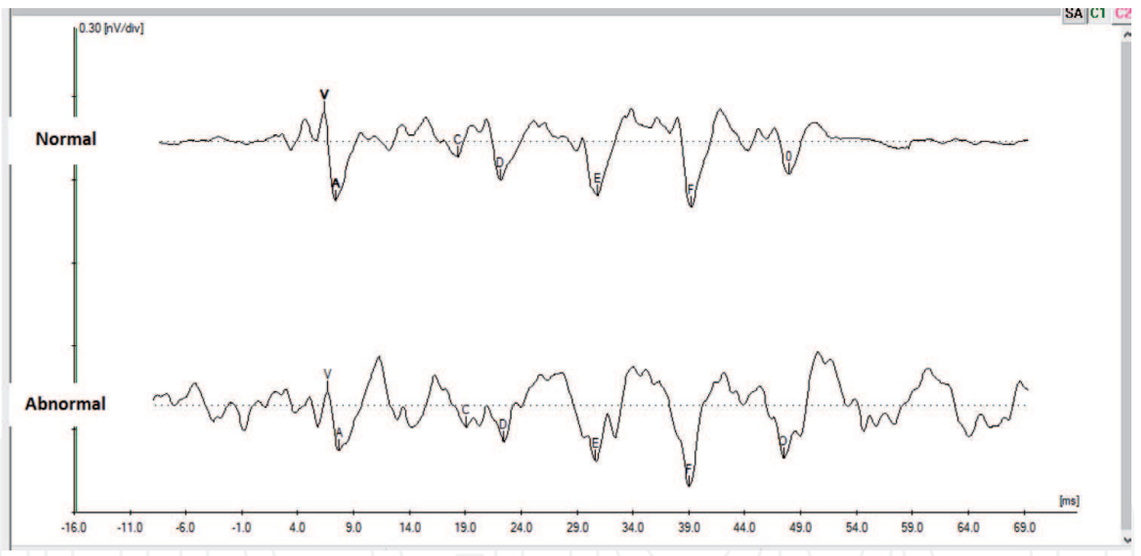

Figure 2.
FFRs of two 9-year-old-children. The top trace represents a normal response and the second represents an abnormal response. Authors' data using BioMARK software and Biologic equipment.

Figure 3 shows an FFR done on an adult aged 25 and on one aged 70. The shape of the FFR is similar in both, but there is an increase in latencies and some waves appear to be absent.

In these FFR tracings, it can be seen that the elderly subject had an increase in latency of all waves compared to the younger adult. Aging causes a progressive loss of structure or functioning of neurons, which can be seen as decreased auditory evoked potentials. Through the FFR, it is seen that there is also a reduction in the speed of neural activation from brainstem to cortical structures.

Our FFR evaluation in adults and the elderly used IHS equipment and the parameters are shown in **Table 14**.

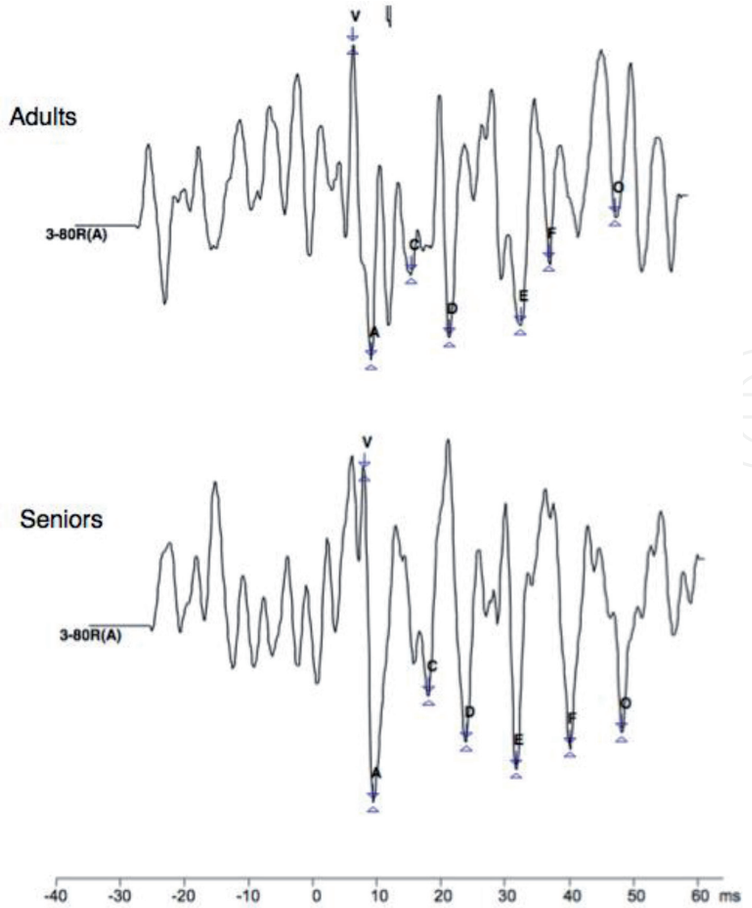

Figure 3.
FFRs of an adult aged 25 years (top) and another aged 70 (bottom). Note the increase in latency of the waves. Authors' data using SmartEP equipment.

Presentation parameters	Setting
Equipment	SmartEP Intelligent Hearing Systems (IHS)
Transducer	Insert phones
Electrodes	Fz, Fpz, M1, M2 or Cz, M1, M2
Stimulation	Right ear
Stimulus	Syllable /da/
Stimulus duration	40 ms
Presentation rate	10.9/s
Window	80–100 ms
Filter	Low pass of 100 Hz and high pass of 2000 Hz Low pass of 100 Hz and high pass of 3000 Hz
Polarity	Alternating
Intensity	80 dBnHL
Number of stimuli	6000
Reproducibility	2 × 3000 stimuli
Condition of evaluation	awake and quiet
Impedance	3k Ohms
Artifact rejection	>10%

Table 14.
Parameters of FFR in adults and the elderly.

6. Conclusion

FFR evaluations can be included as an extra examination in diagnostic testing and have an important role in crosschecking the results. It can also greatly assist making differential diagnoses in different clinical populations. However, each age group has FFRs with specific characteristics, so it is important that the audiologist has access to good normative values for the different age groups (infants and toddlers, young children, children and adolescents, adults and the elderly).

Terminology

10–20 International System	a standard system for electrode location
ABR	auditory brainstem response
AEP	auditory evoked potential. Evoked potential when using an auditory stimulus
BioMARK	Biological Marker of Auditory Processing is software that compares responses from a click to those from a synthetic syllable (usually /da/)
CANS	central auditory nervous system
CAP	central auditory processing
CAPD	central auditory processing disorder
CNS	central nervous system
CV syllable	a phoneme produced by a consonant and a vowel
FFR	frequency following response
Onset portion	the first part of an FFR that reflects the consonant
SAB	Scale of Auditory Behavior, a questionnaire for monitoring auditory processing skills
Sustained portion	the second part of an FFR that reflects the vowel
Synthesized speech	Artificial human speech produced by a computer

Author details

Milaine Dominici Sanfins[1,2*], Michele Vargas Garcia[3], Eliara Pinto Vieira Biaggio[3] and Piotr Henryk Skarzynski[4,5,6]

1 Faculdade de Ciências Médicas, Universidade Estadual de Campinas, Campinas, Brazil

2 Centro de Eletrofisiologia e Neuroaudiologia Avançada, São Paulo, Brazil

3 Departamento de Fonoaudiologia, Universidade Federal de Santa Maria, Santa Maria, Brazil

4 Department of Teleaudiology and Hearing Screening, World Hearing Center, Institute of Physiology and Pathology of Hearing, Warsaw/Kajetany, Poland

5 Department of Heart Failure and Cardiac Rehabilitation, Medical University of Warsaw, Poland

6 Institute of Sensory Organs, Kajetany, Poland

*Address all correspondence to: msanfins@uol.com.br

IntechOpen

References

[1] Johnson KL, Nicol TG, Kraus N. Brainstem response to speech: A biological marker of auditory processing. Ear and Hearing. 2005;**26**(5):424-434

[2] Skoe E, Kraus N. Auditory brainstem response to complex sounds: A tutorial. Ear and Hearing. 2010;**31**:320-324

[3] Anderson S, Parbery-Clark A, White-Schwoch T, Kraus N. Aging affects neural precision of speech encoding. Journal of Neuroscience. 2012;**32**(41):14156-14164

[4] Bidelman GM. Multichannel recordings of the human brainstem frequency-following response: Scalp topography, source generators, and distinctions from the transient ABR. Hearing Research. 2015;**323**:68-80

[5] Sanfins M, Borges L, Donadon C, Hatzopoulos S, Skarzynski P, Colella-Santos M. Electrophysiological responses to speech stimuli in children with otitis media. Journal of Hearing Science. 2017;**7**(4):9-19

[6] Sanfins M, Borges L, Ubiali T, Colella-Santos M. Speech auditory brainstem response (speech ABR) in the differential diagnosis of scholastic difficulties. Brazilian Journal of Otorhinolaryngology. 2017;**83**(1):112-116

[7] Sanguebuche TR, Peixe BP, Bruno RS, Biaggio EPV, Garcia MV. Speech-evoked brainstem auditory responses and auditory processing skills: A correlation in adults with hearing loss. International Archives of Otorhinolaryngology. 2018;**22**(1):38-44

[8] Sanju HK, Mohanan A, Kumar P. Speech-evoked auditory brainstem response in individuals with diabetes mellitus type 2. The Journal of International Advanced Otology. 2017;**13**(1):77-82

[9] Tahaei AA, Ashayeri H, Pourbakht A, Kamali M. Speech evoked auditory brainstem response in stuttering. Scientifica (Cairo). 2014;**2014**:328646

[10] Elkabariti RH, Khalil LH, Husein R, Talaat HS. Speech evoked auditory brainstem response findings in children with epilepsy. International Journal of Pediatric Otorhinolaryngology. 2014;**78**(8):1277-1280

[11] Young E, Sachs M. Representation of steady-state vowels in the temporal aspects of the discharge patterns of populations of auditory-nerve fibers. The Journal of the Acoustical Society of America. 1979;**66**:1381-1403

[12] Russo N, Nicol T, Musacchia G, Kraus N. Brainstem responses to speech syllables. Clinical Neurophysiology. 2004;**115**:2021-2030

[13] Holt L, Lotto A. Speech perception as categorization. Attention, Perception, & Psychophysics. 2012;**72**:1218-1227

[14] McLaughlin S. Introduction to Language Development. Edmond: University of Central Oklahoma; 2007. 508 p

[15] Jeng F, Schnabel E, Dickman B, Ju J, Li X, Lin C, et al. Early maturation of frequency-following response to voice pitch in infants with normal hearing. Perceptual and Motor Skills. 2010;**111**:765-784

[16] Neville H, Bavalier D. Specificity and plasticity in neurocognitive development in humans. In: Gazzaniga M, editor. The New Cognitive Neurosciences. London: Cambridge Mass; 2000

[17] Bellis T. Assessment and Management of Central Auditory Processing Disorders in the Educational Setting. Thomson Delmar Learning: California; 2003

[18] Sano M, Kaga K, Kuan C, Ino K, Mima K. Early myelination patterns in the brainstem auditory nuclei and pathway: MRI evaluation study. International Journal of Pediatric Otorhinolaryngology. 2007;**71**:1105-1115

[19] Skoe E, Krizman J, Anderson S, Kraus N. Stability and plasticity of auditory brainstem function across the lifespan. Cerebral Cortex. 2015;**25**(6):1415-1426

[20] Jeng FC. Infant and childhood development: Intersections between development and language experience. In: Kraus N, Anderson S, White-Schwoch T, Fay R, Popper A, editors. The Frequency-Following Response: A Window into Human Communication. Switzerland: Springer; 2017. pp. 17-43

[21] Picton T, Woods D, Baribeau-Braun J, Healey T. Evoked potential audiometry. The Journal of Otolaryngology. 1977;**6**:90-119

[22] Jeng F, Hu J, Dickman B, Montgomery-Reagan K, Tong M, Wu G, et al. Cross-linguistic comparison of frequency-following responses to voice pitch in American and Chinese neonates and adults. Ear and Hearing. 2011;**32**:699-707

[23] Anderson S, Parbery-Clark A, White-Schwoch T, Kraus N. Development of subcortical speech representation in human infants. The Journal of Acoustical Society of America. 2015;**137**:3346-3355

[24] Jeng F, Peris K, Hu J, Lin C. Evaluation of an automated procedure for detecting frequency-following responses in American and Chinese neonates. Perceptual and Motor Skills. 2013;**116**(2):456-465

[25] Jeng F, Lin C, Chou M, Hollister G, Sabol J, Mayhugh G, et al. Development of subcortical pitch representation in three-month-old chinese infants. Perceptual and Motor Skills. 2016;**122**:123-135

[26] Van Dyke K, Lieberman R, Presacco A, Anderson S. Development of phase locking and frequency representation in the infant frequency-following response. JSLHR. 2017;**60**:2740-2751

[27] Ayas M, Yaseen H, Rajashekhar B. Auditory brainstem processing of complex speech sounds in high risk infants-a preliminary study. International Journal of Current Research and Review. 2015;**7**:22-27

[28] Musacchia G, Ortiz-Mantilla S, Roesler C, Rajendra S, Morgan-Byrne J, Benasich A. Effects of noise and age on the infant brainstem response to speech. Clinical Neurophysiology. 2018;**129**:2623-2634

[29] Gabriel L, Vernier L, Ferreira M, Silveira A, Machado M. Parameters for applying the brainstem auditory evoked potential with speech stimulus: Systematic review. International Archives of Otorhinolaryngology. 2018;**22**(4):460-468

[30] Sanfins M. Electrophysiological Evaluation with Verbal and Non-verbal Sounds in Children with a History of Otitis Media. State University of Campinas; 2017. Available from: http://www.repositorio.unicamp.br/handle/REPOSIP/330747

[31] Hornickel J, Lin D, Kraus N. Speech-evoked auditory brainstem responses reflect familial and cognitive influences. Developmental Science. 2013;**16**(1):101-110

[32] Cacace AT, McFarland DJ. Central auditory processing disorder in school-aged children: A critical review. Journal of Speech, Language, and Hearing Research. 1998;**41**(2):355-373

[33] Johnson K, Nicol T, Zecker S, Kraus N. Developmental plasticity

in the human auditory brainstem. The Journal of Neuroscience. 2008;**28**(15):4000-4007

[34] Kraus N, Hornickel J. cABR: A biological probe of auditory processing. In: Geffner DS, Ross-Swain D, editors. Auditory Processing Disorders: Assessment, Management, and Treatment. 2a ed. San Diego: Plural Publishing; 2013. pp. 159-183

[35] Anderson S, Parbery-Clark A, White-Schwoch T, Drehobl S, Kraus N. Effects of hearing loss on the subcortical representation of speech cues. The Journal of the Acoustical Society of America. 2013;**133**(5):3030-3038

[36] Hornickel J, Kraus N. cABR can predict auditory-based communication skills. The Hearing Journal. 2012;**65**:28-30

[37] Vander Werff KR, Burns KS. Brain stem responses to speech in younger and older adults. Ear and Hearing. 2011;**32**(2):168-180

[38] Benasich A, Fitch R. Developmental Dyslexia: Early Precursors, Neuro-behavioral Markers and Biological Substrates. Baltimore: Brookes Publishing; 2012

[39] Bogliotti C, Serniclaes W, Messaoud-Galusi SLSC. Discrimination of speech sounds by children with dyslexia: Comparisons with chronological age and reading level controls. Journal of Experimental Child Psychology. 2008;**101**:137-155

[40] Kumar P, Singh NK. BioMARK as electrophysiological tool for assessing children at risk for (central) auditory processing disorders without reading deficits. Hearing Research. 2015;**324**:54-58

[41] Song JH, Nicol T, Kraus N. Test-retest reliability of the speech-evoked auditory brainstem response. Clinical Neurophysiology. 2011;**122**(2):346-355

[42] Krizman J, Marian V, Shook A, Skoe E, Kraus N. Subcortical encoding of sound is enhanced in bilinguals and relates to executive function advantages. Proceedings of the National Academy of Sciences. 2012;**109**(20):7877-7881

[43] Krizman J, Skoe E, Kraus N. Bilingual enhancements have no socioeconomic boundaries. Developmental Science. 2016;**19**(6):881-891

[44] Patel A, Peretz I, Tramo M, Labrecque R. Processing prosodic and music pattern: A neurophsychological investigation. Brain and Language. 1998;**61**:123-144

[45] Russo N, Skoe E, Trommer B, Nicol T, Zecker S, Bradlow A, et al. Deficient brainstem encoding of pitch in children with autism spectrum disorders. Clinical Neurophysiology. 2008;**119**(8):1720-1731

[46] Wible B, Nicol T, Kraus N. Abnormal neural encoding of repeated speech stimuli in noise in children with learning problems. Clinical Neurophysiology. 2002;**113**:484-494

[47] Cunningham J, Nicol T, Zecker S. Neurobiologic responses to speech in noise in children with learning problems: Deficits and strategies for improvement. Clinical Neurophysiology. 2001;**112**:758-767

[48] Ladefoged P. A Course in Phonetics. Boston: Thomson Higher Learning; 2006

[49] Peixe BP, Silva DD, Biaggio EPV, Bruno RS, Sanguebuche TR, Garcia MV. Applicability of evoked auditory brainstem responses with complex stimuli in adults with hearing loss. International Archives of Otorhinolaryngology. 2018;**22**(3):239-244

[50] Sinha S, Basavaraj V. Speech evoked auditory brainstem responses: A new

tool to study brainstem encoding of speech sounds. Indian Journal of Otolaryngology and Head & Neck Surgery. 2010;**62**(4):395-399

[51] Schoof T, Rosen S. The role of auditory and cognitive factors in understanding speech in noise by normal-hearing older listeners. Frontiers in Aging Neuroscience. 2014;**6**:307

[52] Palmer SB, Musiek FE. Electrophysiological gap detection thresholds: Effects of age and comparison with a behavioral measure. Journal of the American Academy of Audiology. 2014;**25**(10):999-1007

[53] Lin F, Ferrucci L, Metter E, Um Y, Zonderman A, Resnick S. Hearing loss and cognition in the Baltimore longitudinal study of aging. Neuropsychology. 2011;**25**:763-770

[54] Sanfins M, Colella-Santos M. A review of the clinical applicability of speech-evoked auditory brainstem responses. The Journal of Health Science. 2016;**6**(1):9-16

[55] Ahadi M, Pourbakht A, Jafari AH, Jalaie S. Effects of stimulus presentation mode and subcortical laterality in speech-evoked auditory brainstem responses. International Journal of Audiology. 2014;**53**(4):243-249

[56] Anderson S, Parbery-Clark A, White-Schwoch T, Kraus N. Auditory brainstem response to complex sounds predicts self-reported speech-in-noise performance. Journal of Speech Language and Hearing Research. 2013;**56**(1):31-43

[57] Clinard C, Tremblay K. Aging degrades the neural encoding of simple and complex sounds in the human brainstem. Journal of the American Academy of Audiology. 2013;**24**(7):590-599