Published in final edited form as:

J Matern Fetal Neonatal Med. 2011 October ; 24(0 1): 151–153. doi:10.3109/14767058.2011.607614.

A sensitive period for cochlear implantation in deaf children

Anu Sharma, Ph.D and Julia Campbell, Au.D

Brain and Behavior Laboratory, University of Colorado at Boulder

Introduction

Approximately 2 children per 1000 are born with sensorineural hearing loss. These children have varying degrees of deafness, and those who are at high risk of developing impaired speech and oral language, and who meet the candidacy criteria, are fitted with cochlear implants. A cochlear implant (CI) is a biomedical device that is surgically implanted in the cochlea of a deaf child and provides direct stimulation to the auditory nerve and brain. The electrical stimulation provided by the CI differs in principle from acoustic stimulation, however, it allows the implant recipient to differentiate speech sounds and interpret acoustic input in a meaningful manner, thereby facilitating the acquisition of speech and language. Worldwide there are approximately ~70,000 infants and children fitted with CIs.

During the first few years of life, the developing brain largely depends on external stimulation to form meaningful neural connections and a functional network, which can support behavioral learning (Hubel & Wiesel, 1970; Pallas, 2001). When sensory input such as hearing is absent, the consequences on brain development can be devastating. Animal studies have shown that deafness during the first few years of life significantly affects auditory cortical development, in that synaptogenesis (the creation of neuronal connections) and maturation of cortical layers is both delayed and abnormal (Klinke et al., 1999; Kral et al., 2000, 2001). The development of lower-level subcortical structures still occurs in deafness, but further development of neuronal connections and synaptic firing in the cortex is altered and later becomes non-existent as age increases (Klinke et al., 1999; Kral et al., 2000, 2001). In humans, similar results have been found using cortical auditory evoked potentials (CAEPs) via non-invasive electroencephalography (EEG) (Eggermont et al., 1997; Ponton et al., 1996). Normal auditory responses from the brain are either delayed or non-existent in deaf humans, indicating that brain maturation is highly dependent upon appropriate stimulation (Eggermont & Ponton, 2003). A cochlear implant can provide a deaf child with the stimulation necessary for the central auditory pathways to develop. As we will describe, cochlear implantation which occurs within a development time period of maximal neuronal plasticity, i.e., a sensitive period, results in the most optimal outcomes for the implanted child.

An important question in the field of deafness and cochlear implants is: When is the most optimal time to fit a young deaf child with a cochlear implant? In other words, at what age will implantation provide the best possibility for development of speech and language skills? In this review, we present evidence relating to a sensitive period for auditory brain development in cochlear implanted children and discuss consequences of implantation outside of the sensitive period relating to cortical re-organization.

A sensitive period for cochlear implantation

Sensitive periods in the cortex exist due to heightened levels of neuroplasticity. Neuroplasticity, or the ability of the brain to adapt in response to incoming sensory input, is quite high during the first few years of life, due in part to a major increase in synaptogenesis (Huttenlocher & Dabholkar, 1997). One way of examining the time limits for plasticity in

the human central auditory system is the use of cortical auditory evoked potentials (CAEPs). In particular, the latency (time it takes for the brain to respond to stimulation) of the P1 component of the CAEP decreases systematically as a function of age. This decrease in latency is a result of the refinement and maturation of the central auditory pathways as the system develops. Synaptogenesis, pruning, and myelination all contribute to this faster and more efficient transmission of sound (Eggermont & Ponton, 2003). Because the latency of the P1 peak decreases as age increases, this component of the CAEP acts as a biomarker of auditory cortical development.

The P1 response has been measured in deaf children who received CIs at different ages in order to examine the limits of plasticity in the central auditory system (Ponton et al., 1996; Sharma et al., 2002a, 2002b, 2002c, 2005a, 2005b, 2007, 2009; Sharma & Dorman 2006). Studies from our laboratory have examined P1 latency in 245 congenitally deaf children fit with a CI (Sharma et al., 2002a, 2002b, 2002c; Sharma & Dorman, 2006) and found that children who received stimulation via a CI early in childhood (<3.5 years) had normal P1 latencies within 6 months of implant use, while children who received CI stimulation late in childhood (>7 years) showed abnormal cortical response latencies even after years of implant use. A group of children receiving CIs between 3.5 and 7 years revealed highly variable response latencies. Overall, our P1 data suggest a sensitive period for optimal central auditory development of about 3.5 years in childhood. Though there is some variability in the data from ages 3.5 to 7 years, the sensitive period ends at approximately age 7 years. This finding of a sensitive period for central auditory development in humans is consistent with other studies of PET scan brain imaging in cochlear implanted children (Lee et al., 2001), evoked potential recordings (Eggermont & Ponton 2003) behavioral measures (Schorr et al., 2005) and from recordings in congenitally deaf animals (Kral et al, 2000; 2001; 2007 Ryugo et al., 1997). Speech and language studies have consistently shown that children implanted under age 3–4 years show significantly better speech and language skills than children implanted after 6–7 years (Geers, 2006; Kirk et al., 2002). In general, implantation at younger ages results in better speech and language outcomes for cochlear implanted children (Holt & Svirsky, 2008; Nicholas & Geers, 2007). As a result, in the United State Food and Drug Administration (FDA) has approved cochlear implantation at ~12 months of age.

Consequences of deafness beyond the sensitive period

A consequence of absent or significantly delayed auditory input to the brain is a re-organization between sensory systems (cross-modal re-organization). Thus, cochlear implantation within the sensitive period for auditory cortical development is critical not only for optimal speech and language development, but also to prevent re-organization of the cortex, which can limit the capacity for oral language learning. Animal studies suggest that at the end of the sensitive period the primary auditory cortex may be partially or completely disconnected (de-coupled) from surrounding higher-order cortex including language cortex (Kral, 2007). This leaves higher-order auditory cortex susceptible to recruitment from other sensory modalities. For example, in long-term deafened adults, it has been shown that visual and somatosensory processing may take place in auditory cortical areas (Buckley & Tobey, 2011; Finney et al., 2001; Neville et al., 1983; Sharma et al., 2007). Functionally, such cross-modal re-organization may result in enhanced processing for various aspects of the recruiting modality, as seen in greater attention to peripheral visual information in deaf individuals (Baverlier et al., 2000; Lomber et al., 2010; Neville & Lawson, 1987), while leaving significant deficits in auditory and multimodal processing, as seen in impaired auditory processing and auditory-visual integration (Gilley et al., 2010; Schorr et al., 2005).

Summary

Deafness and hearing loss during the first few years of life has negative consequences for the developing brain. Cochlear implantation bypasses the inner ear, providing direct stimulation to the central auditory pathways. Our studies show that the optimal time to implant a young deaf child is within a sensitive period of ~ age 3.5 years in childhood (best by the first two years of life). After the overall sensitive period ends (~ age 7 years), there is a high likelihood of de-coupling of primary cortical areas from surrounding higher-order cortex and subsequent cross-modal recruitment of the higher-order auditory cortical areas by other modalities such as vision and somatosensation. Thus, implantation within the sensitive period allows for normal auditory cortical maturation, providing ample opportunity for appropriate acquisition of speech and oral language.

References

- Buckley KA, Tobey EA. Cross-modal plasticity and speech perception in pre- and postlingually deaf cochlear implant users. *Ear Hear.* 2011; 32(1):2–15. [PubMed: 20829699]
- Eggermont JJ, Ponton CW. Auditory-evoked potential studies of cortical maturation in normal hearing and implanted children: correlations with changes in structure and speech perception. *Acta Otolaryngol.* 2003; 123(2):249–252. [PubMed: 12701751]
- Eggermont JJ, Ponton CW, Don M, Waring MD, Kwong B. Maturation delays in cortical evoked potentials in cochlear implant users. *Acta Otolaryngol.* 1997; 117(2):161–163. [PubMed: 9105439]
- Finney EM, Fine I, Dobkins KR. Visual stimuli activate auditory cortex in the deaf. *Nat Neurosci.* 2001; 4(12):1171–1173. [PubMed: 11704763]
- Geers AE. Factors influencing spoken language outcomes in children following early cochlear implantation. *Adv Otorhinolaryngol.* 2006; 64:50–65. [PubMed: 16891836]
- Gilley PM, Sharma A, Mitchell TV, Dorman MF. The influence of a sensitive period for auditory-visual integration in children with cochlear implants. *Restor Neurol Neurosci.* 2010; 28(2):207–218. [PubMed: 20404409]
- Holt RF, Svirsky MA. An exploratory look at pediatric cochlear implantation: is earliest always best? *Ear Hear.* 2008; 29(4):492–511. [PubMed: 18382374]
- Huttenlocher PR, Dabholkar AS. Regional differences in synaptogenesis in human cerebral cortex. *J Comp Neurol.* 1997; 387(2):167–178. [PubMed: 9336221]
- Kirk KI, Miyamoto RT, Lento CL, Ying E, O'Neill T, Fears B. Effects of age at implantation in young children. *Ann Otol Rhinol Laryngol Suppl.* 2002; 189:69–73. [PubMed: 12018353]
- Klinke R, Kral A, Heid S, Tillein J, Hartmann R. Recruitment of the auditory cortex in congenitally deaf cats by long-term cochlear electrostimulation. *Science.* 1999; 285(5434):1729–1733. [PubMed: 10481008]
- Kral A. Unimodal and cross-modal plasticity in the 'deaf' auditory cortex. *Int J Audiol.* 2007; 46(9):479–493. [PubMed: 17828664]
- Kral A, Eggermont JJ. What's to lose and what's to learn: development under auditory deprivation, cochlear implants and limits of cortical plasticity. *Brain Res Rev.* 2007; 56(1):259–269. [PubMed: 17950463]
- Kral A, Hartmann R, Tillein J, Heid S, Klinke R. Congenital auditory deprivation reduces synaptic activity within the auditory cortex in a layer-specific manner. *Cereb Cortex.* 2000; 10(7):714–726. [PubMed: 10906318]
- Kral A, Hartmann R, Tillein J, Heid S, Klinke R. Delayed maturation and sensitive periods in the auditory cortex. *Audiol Neurotol.* 2001; 6(6):346–362. [PubMed: 11847463]
- Lee DS, Lee JS, Oh SH, Kim SK, Kim JW, Chung JK, Lee MC, Kim CS. Cross-modal plasticity and cochlear implants. *Nature.* 2001; 409(6817):149–150. [PubMed: 11196628]
- Lomber SG, Meredith MA, Kral A. Cross-modal plasticity in specific auditory cortices underlies visual compensations in the deaf. *Nat Neurosci.* 2010; 13(11):1421–1427. [PubMed: 20935644]

- Neville HJ, Lawson D. Attention to central and peripheral visual space in a movement detection task: an event-related potential and behavioral study. II. Congenitally deaf adults. *Brain Res.* 1987; 405(2):268–283. [PubMed: 3567605]
- Neville HJ, Schmidt A, Kutas M. Altered visual-evoked potentials in congenitally deaf adults. *Brain Res.* 1983; 266(1):127–132. [PubMed: 6850339]
- Nicholas JG, Geers AE. Will they catch up? The role of age at cochlear implantation in the spoken language development of children with severe to profound hearing loss. *J Speech Lang Hear Res.* 2007; 50(4):1048–1062. [PubMed: 17675604]
- Pallas SL. Intrinsic and extrinsic factors that shape neocortical specification. *Trends Neurosci.* 2001; 24(7):417–423. [PubMed: 11410273]
- Ponton CW, Don M, Eggermont JJ, Waring MD, Masuda A. Maturation of human cortical auditory function: differences between normal-hearing children and children with cochlear implants. *Ear Hear.* 1996; 17(5):430–437. [PubMed: 8909891]
- Ryugo DK, Pongstaporn T, Huchton DM, Niparko JK. Ultrastructural analysis of primary endings in deaf white cats: morphologic alterations in endbulbs of Held. *J Comp Neurol.* 1997; 385(2):230–244. [PubMed: 9268125]
- Schorr EA, Fox NA, van Wassenhove V, Knudsen EI. Auditory-visual fusion in speech perception in children with cochlear implants. *Proc Natl Acad Sci U S A.* 2005; 102(51):18748–18750. [PubMed: 16339316]
- Sharma A, Dorman MF. Central auditory development in children with cochlear implants: clinical implications. *Adv Otorhinolaryngol.* 2006; 64:66–88. [PubMed: 16891837]
- Sharma A, Kraus N, McGee TJ, Nicol TG. Developmental changes in P1 and N1 central auditory responses elicited by consonant-vowel syllables. *Electroenceph and Clin Neurophys.* 1997; 104(6):540–545.
- Sharma A, Dorman M, Spahr A, Todd NW. Early cochlear implantation in children allows normal development of the central auditory pathways. *Ann Otol Rhinol Laryngol Suppl.* 2002a; 189:38–41. [PubMed: 12018346]
- Sharma A, Dorman MF, Spahr AJ. A sensitive period for the development of the central auditory system in children with cochlear implants: implications for age of implantation. *Ear Hear.* 2002b; 23(6):532–539. [PubMed: 12476090]
- Sharma A, Dorman MF, Kral A. The influence of a sensitive period on central auditory development in children with unilateral and bilateral cochlear implants. *Hear Res.* 2005a; 203(1–2):134–143. [PubMed: 15855038]
- Sharma A, Martin K, Roland P, Bauer P, Sweeney MH, Gilley P, Dorman M. P1 latency as a biomarker for central auditory development in children with hearing impairment. *J Am Acad Audiol.* 2005b; 16(8):564–573. [PubMed: 16295243]
- Sharma A, Gilley PM, Dorman MF, Baldwin R. Deprivation-induced cortical reorganization in children with cochlear implants. *Int J Audiol.* 2007; 46(9):494–499. [PubMed: 17828665]
- Sharma A, Nash AA, Dorman M. Cortical development, plasticity and re organization in children with cochlear implants. *J Commun Disord.* 2009; 42(4):272–279. [PubMed: 19380150]