

# Cortical plasticity and reorganization in hearing loss

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Hearing-impaired adults and children who receive intervention with hearing aids and cochlear implants provide a platform to examine the trajectories and characteristics of deprivation-induced and experience-dependent plasticity in the central auditory system. We review the evidence for sensitive periods for development of the central auditory pathways. A sensitive period in early childhood appears to coincide with the period maximal synaptogenesis in the auditory cortex. Implantation within this sensitive period provides the auditory experience needed for refinement of essential synaptic pathways. Cross-modal recruitment is another aspect of plasticity that is apparent in deaf children. In long-term congenital deafness, somatosensory and visual stimuli activate higher-order auditory areas. Overall, it appears that the functional activation of cognitive circuitry resulting from cortical reorganization in deafness is predictive of outcomes after intervention. A better understanding of cortical development and reorganization in auditory deprivation has important implications for optimal intervention and habilitation of these patients.

## DEVELOPMENT AND CORTICAL AUDITORY EVOKED POTENTIALS

### Normal trajectory of central auditory system development

Cortical auditory evoked potentials (CAEPs) are averaged electroencephalography recordings of cortical brain activity in response to sound. With age, CAEP waveforms undergo major morphological changes. In infants, the response is dominated by a large, broad positivity referred to as the P1 component. As a child ages, an invagination known as the N1 and a second positive peak called the P2 appears (Sharma *et al.*, 2007). These new components can be observed in children as young as 3 to 5 years using slow stimulation rates and are consistent by preadolescence at standard stimulation rates (Gilley *et al.*, 2006).

Latency of the P1 response represents the summation of the synaptic delays throughout the central and peripheral auditory pathways (Eggermont *et al.*, 1997). In normal-hearing children, it decreases systematically and chronically with age and thus it has been used as a biomarker for auditory brain maturation (Sharma *et al.*, 2002a). Sharma and colleagues (2002b) established norms for typical P1 latency as a function of age. The P1 component occurs around 300 milliseconds in newborns then rapidly decreases over the first years of life to a latency of around 125 milliseconds in 3-year-olds. Afterwards, latency levels off at about 60 milliseconds

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in adults. Auditory thalamic and cortical sources have been identified as generators and it has been suggested that P1 represents the first recurrent auditory cortex activity (Liegeois-Chauvel *et al.*, 1994; Kral and Eggermont, 2007).

### **Effects of deprivation**

Congenitally-deaf cats are commonly used to study the effects of auditory deprivation on the brain. Kral *et al.* (2000) demonstrated layer-specific deficits in synaptic activity in electrically-stimulated deaf cats compared with hearing cats and proposed that similar deficits were likely in deaf children. As predicted, the research in cats shows significant parallels with results in humans (Kral and Sharma, 2012). A significant delay was found in the P1 latencies of prelingually deafened cochlear-implant users compared to age-matched normal-hearing subjects (Ponton *et al.*, 2000a,b; Eggermont and Ponton, 2002; 2003). Interestingly, Ponton and colleagues also found that after cochlear implantation, there is clear evidence of cortical maturation, suggesting that for the first few years of life the potential for normal auditory development is maintained in deaf children.

### **A SENSITIVE PERIOD FOR AUDITORY DEVELOPMENT**

In a study of 104 (later 235) congenitally-deaf children, those who were fitted with cochlear implants before approximately 3.5 years had age-appropriate P1 response latencies within 6 months while those with periods of deprivation of more than 7 years had abnormal CAEP responses. Children with an intermediate deprivation duration — between 3.7 and 7 years — showed a more variable performance (Sharma *et al.*, 2002a, 2009). These results suggest that the auditory system has a sensitive period of optimal plasticity up until 3.5 years of deprivation. Plasticity decreases after that age, but does remain in some children up to age 7. These results point to the importance of early implantation within the 3.5 year period. Indeed, the approved clinical guideline has moved from age 4 in 1990 to 12 months presently, taking maximal advantage of a highly plastic central auditory system in early childhood. Interestingly, the established sensitive period cut-offs correspond to the end of the period of synaptic overshoot at approximately age 3.5 to 4 years (Conel, 1939-1967; Huttenlocher and Dabholkar, 1997; Kral and Eggermont, 2007) and the development of adult-like myelin by age 7 to 8 (Su *et al.*, 2009; Eggermont and Moore, 2012). Implantation within this brief sensitive period provides the auditory experience needed for the establishment and refinement of essential synaptic pathways necessary for auditory-based learning to occur.

### **CORTICAL REORGANIZATION FOLLOWING SENSORY DEPRIVATION**

#### **Cross-modal reorganization in hearing loss**

Research indicates that auditory deprivation persisting beyond the end of the sensitive period may facilitate a functional decoupling of primary auditory cortex from higher-order auditory cortex. In deaf cats implanted at the end of the sensitive period (approximately 4 months), a delay of activation of supragranular layers of the

cortex and reduced activation at infragranular layers (V and VI) has been demonstrated when compared to normal-hearing cats (Kral *et al.*, 2000, 2002, 2005, 2006). These changes suggest deficient or partial development of inhibitory synapses between layer IV and supragranular layers (Kral *et al.*, 2000, 2002, 2005, 2006). Such a partial or complete decoupling between primary auditory cortex and secondary auditory cortex is also supported by FDG-PET imaging studies demonstrating decreased functional connectivity of primary auditory cortex to adjacent regions in older compared to younger pre-lingually deaf children (Kang *et al.*, 2003). The fact that a majority of children implanted after the sensitive period never develop a normal N1 CAEP response while children implanted before the age of 3.5 demonstrate an N1 response with normal morphology and latency further substantiates the decoupling hypothesis (Sharma and Dorman, 2006). Since the N1 component is presumed to arise from secondary auditory cortex, a missing N1 response would indicate improper cortico-cortical activation between primary and secondary auditory cortices (Kral and Eggermont, 2007; Kral and Sharma, 2012)

While primary auditory cortex may still retain basic facilities to process auditory information, higher-order representations linked to incoming auditory stimuli may not be effectively established if top-down modulatory processing is altered (Kral *et al.*, 2001, 2005). Because these top-down cortico-cortical pathways provide modulatory feedback, such a decoupling between primary and higher-order auditory areas may significantly affect perception as well as learning.

Given that higher-order cortex is multi-modal in nature, a decoupling between primary and secondary auditory cortex may also lead to extensive cross-modal reorganization. In the case of auditory deprivation persisting beyond the sensitive period, there is evidence that higher-order auditory areas may be re-purposed by other sensory modalities such as vision (Nishimura *et al.*, 1999; Bavelier and Neville, 2002; Lee *et al.*, 2003) and somatosensation (Sharma *et al.*, 2007). This is corroborated by evidence of atypically-distributed networks in multi-modal auditory areas in late-implanted children (Gilley *et al.*, 2006). It is well documented that early-implanted children demonstrate better speech and language outcomes relative to children implanted after age 6 to 7 years, and it has been suggested that changes in neural resource allocation (i.e., cross-modal recruitment by other sensory modalities) may indeed explain poorer behavioural outcomes with implants associated with late-implanted children (Svirsky *et al.*, 2004; Doucet *et al.*, 2006; Geers, 2006).

More recently, signs of cross-modal plasticity have been indicated within the context of adult hearing impairment. Animal studies suggest that inputs from other sensory modalities may significantly influence neurons in auditory areas, which may account for some of the functional deficits observed in adult implant and hearing-aid users. For instance, an increase in multisensory neurons in the auditory cortex and anterior auditory field in adult ferrets with moderate hearing loss compared to normal-hearing adult ferrets suggests that cross-modal reorganization may facilitate compensatory plasticity, negatively affecting important processes necessary to speech understanding such as multisensory integration (Meredith *et al.*, 2012). In

this sense, cross-modal reorganization may at least partially explain poorer outcomes associated with this population of late-deafened adults who receive cochlear implants.

## **CLINICAL APPLICATIONS OF THE P1**

There is an abundance of research supporting the clinical utility of the P1 biomarker of central auditory maturation in children (Rance *et al.*, 2002; Golding *et al.*, 2007; Pearce *et al.*, 2007; Cardon *et al.*, 2012; Cardon and Sharma, 2013). Because normal P1 latency varies as a function of age, normative data provide a standard from which P1 responses in congenitally deaf children and congenitally-deaf children fit with cochlear implants at various ages can be evaluated (Sharma *et al.*, 2002b).

The P1 biomarker can serve as an objective candidacy and/or outcome measure for children who receive hearing aids or cochlear implants. For example, Sharma *et al.* (2005) used P1 latency to determine the benefit of hearing aids in hearing-impaired children. If P1 latency was within normal limits for the child's age, then it was assumed that the hearing aid was providing sufficient stimulation for normal development of auditory pathways. However, if P1 latency did not decrease after regular hearing-aid use, then other options such as alternative hearing-aid settings or cochlear implants were considered. Thus, the P1 biomarker may aid in the clinical decision-making process, particularly in determination of cochlear-implant candidacy. Similarly, the P1 can be used as an outcome measure in children fit with hearing aids and cochlear implants. Tracked over time, the P1 can be used to evaluate the developmental progress of the cortical maturation in these children after receiving intervention (Sharma *et al.*, 2002a; 2009).

In special cases like auditory neuropathy spectrum disorder (ANSD), cortical auditory development can be assessed by examination of the P1 CAEP. Recent findings from our laboratory suggest a shorter sensitive period (approximately 2 years) for central auditory maturation after cochlear implantation in children with ANSD as compared to the sensitive period for congenitally-deaf children (i.e., 3.5 years) reviewed earlier (Cardon and Sharma, 2013). Therefore, in children with ANSD the P1 response may be especially important in the evaluation of efficacy of intervention. Moreover, it is very possible that ANSD and other disorders of the nervous system that co-exist with hearing loss (i.e., Fragile X Syndrome and Rett's Syndrome) may alter sensitive periods given developmental differences in underlying neuronal maturation. A clearer understanding of the existence and time courses of P1 development in this population may lead to improved intervention and treatment options for these children (Sharma *et al.*, 2013). While the existence and difference in sensitive periods for these individual disorders are not well understood, the P1 biomarker nevertheless provides normative data against which the developmental trajectories of children with these disorders receiving various forms of intervention can be assessed.

It is well documented that children with multiple disabilities account for a substantial percentage of children with hearing loss (Fortnum *et al.*, 2002). Many of

these children are also difficult to condition to traditional behavioural threshold techniques (i.e., visual reinforcement audiometry). Often, life-threatening co-morbid health conditions make obtaining thresholds via auditory brainstem response (ABR) difficult to perform in this population since sedation under anaesthesia is not a viable option (Edwards, 2007). Additionally, as a significant proportion of children with multiple handicaps concomitant with hearing loss who receive cochlear implants never achieve closed- or open-set speech discrimination abilities, the ability to document outcomes post-intervention is additionally limited (Trimble *et al.*, 2008). While the resolution to implant a child with multiple disabilities is a multi-sided decision in which the complex medical, social-emotional, and developmental needs of the child need to be considered, the P1 CAEP response is non-invasive, easy to record, requires no anaesthesia, and proves a useful tool in assessing developmental status, hearing-aid benefit, and cochlear-implant outcomes in these cases (Sharma *et al.*, 2013).

## **CASE STUDY**

In the next section of this paper, a case study demonstrating the clinical capability of the P1 biomarker in objectively assessing cochlear-implant outcomes will be presented.

### **Procedures**

The stimulus used to elicit the CAEP response was a speech syllable /ba/ presented at a comfortable level through a speaker located at 45 degrees azimuth at a suprathreshold level. All testing took place in an electromagnetically-shielded sound booth. The subject was seated comfortably in a reclining chair during the recording and was allowed to watch a video or cartoon of her choice with the audio muted. For all testing, the subject's cochlear implants were set to their usual settings.

CAEPs were recorded using a standard electrode montage, recording parameters, and test procedures used routinely in our laboratory and outlined in previous studies (Sharma *et al.*, 1997; Sharma *et al.*, 2002a; 2002b). Cochlear-implant electrical artifact was removed via a common mode rejection technique detailed in a study from our group (Gilley *et al.*, 2006). The latency of the P1 component of the CAEP response was identified using the grand average waveforms for each subject.

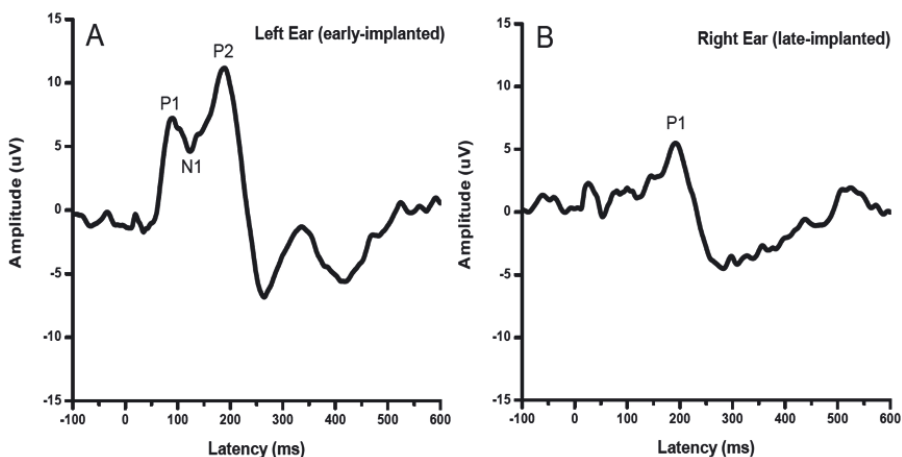
### **Results**

The subject was a female child identified with a bilateral hearing loss at age 27 months following a case of spinal meningitis at age 10 to 12 months. The child's hearing loss was progressive in nature. She received bilateral cochlear implants sequentially, the first implant in her left ear at age 32 months and her second implant around age 5.

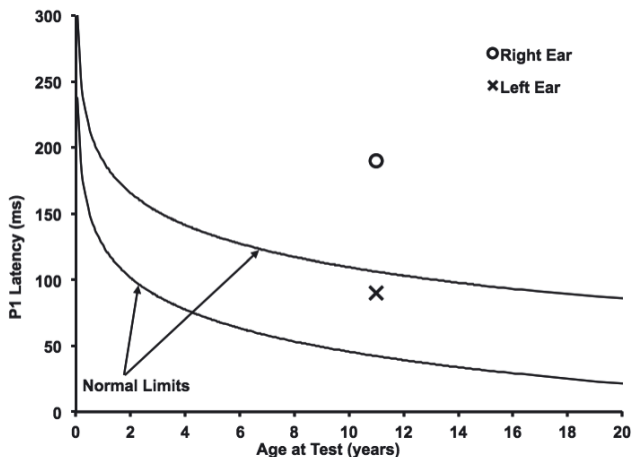
In this case of a child who received cochlear implants sequentially, P1 responses were used to evaluate whether the implant was allowing for normal cortical auditory maturation. CAEP responses using the P1 biomarker were recorded at age 11 years.

As seen in Fig. 1A, a robust P1 response was present. The latency of the P1 response in the left ear fell within the 95% confidence intervals for normal development of the P1 response, indicating age-appropriate development of the central auditory pathway (Fig. 2). This robust P1 response with normal latency and morphology for the left ear clearly demonstrates that the left implant is providing adequate stimulation for cortical auditory development. These findings are consistent with the fact that the child received her left cochlear implant within the sensitive period as well as behavioural results from the child's audiologist indicating that the subject performs better on speech perception measures in the right implanted ear.

As shown in Fig. 1B, a P1 response recorded via stimulation of the right ear was present, but with a morphology that is not appropriate given the child's age. The latency of the P1 response in the right ear fell outside of normal limits, indicating abnormal or delayed development of the central auditory pathway. While the presence of a P1 response indicates that the right cochlear implant is providing adequate stimulation, the morphology of this response was not age-appropriate, likely due to the fact that the child was implanted at the end of the sensitive period around age 5. These results are consistent with findings from Sharma *et al.* (2005) which showed that cochlear implantation in one ear may not necessarily facilitate an extended sensitive period in the later implanted ear.



**Fig. 1:** Grand average CAEP response in the early-implanted left ear (top) and the late-implanted right ear (bottom) for 11-year-old sequentially-implanted subject.



**Fig. 2:** Average P1 latency as a function of child’s age plotted against 95% confidence limits for normal-hearing children for 11-year-old sequentially-implanted subject.

## FUTURE DIRECTIONS

The P1 biomarker has proven to have real clinical value in assessing central auditory development following intervention via hearing aids and cochlear implants in congenitally-deaf children, children with ANSD, and children with multiple disabilities concomitant with hearing loss. The P1 response has great clinical capability of providing a measure of cortical auditory development, with potential applications in cochlear-implant candidacy and objective outcomes following intervention via hearing aids or cochlear implants. The maladaptive consequences of cross-modal reorganization in hearing loss are still not well understood. Future research should focus on grasping such cross-modal auditory-visual and auditory-somatosensory changes that take place in a deprived auditory system and the extent to which these changes are reversible following treatment and/or intensive rehabilitation, as findings from these studies may contribute to better outcomes for some children with hearing loss who receive intervention. Though differences in the time window of central auditory plasticity has been documented in specific cases such as ANSD, a clearer understanding of differences in sensitive periods in cases of specific disabilities is critically lacking. This knowledge may help us better understand variable outcomes in implanted children and may lead to more timely intervention for this population.

## REFERENCES

- Bavelier, D., and Neville, H. (2002). "Cross-modal plasticity: where and how?" *Nat. Rev. Neurosci.*, **3**, 443-452.
- Cardon, G., Campbell, J., and Sharma, A. (2012). "Plasticity in the developing auditory cortex: evidence from children with sensorineural hearing loss and auditory neuropathy spectrum disorder," *J. Am. Acad. Audiol.*, **23**, 396-411.
- Cardon G, and Sharma, A. (2013). "Central auditory maturation and behavioral outcome in children with auditory neuropathy spectrum disorder who use cochlear implants," *Int. J. Audiol.*, **52**, 577-586.
- Conel, J. (1939-1967). *The Post-Natal Development of Human Cerebral Cortex*, Vols. I-VIII (Cambridge, MA: Harvard University Press).
- Doucet, M., Bergeron, F., Lassonde, M., Ferron, P., and Lepore, F. (2006). "Cross-modal reorganization and speech perception in cochlear implant users." *Brain*, **129**, 3376-3383.
- Edwards, L.C. (2007). "Children with cochlear implants and complex needs: a review of outcome research and psychological practice," *J. Deaf Stud. Deaf Edu.*, **12**, 258-268.
- Eggermont, J., Ponton, C., Don, M., Waring, M., and Kwong, B. (1997). "Maturation delays in cortical evoked potentials in cochlear implant users," *Acta Oto-Laryngol.*, **117**, 161-163.
- Eggermont, J., and Ponton, C. (2002). "The neurophysiology of auditory perception: From single units to evoked potentials," *Audiol. Neuro-Otol.*, **7**, 71-99.
- Eggermont, J., and Ponton, C. (2003). "Auditory-evoked potential studies of cortical maturation in normal hearing and implanted children: Correlations with changes in structure and speech perception," *Acta Oto-Laryngol.*, **123**, 249-252.
- Eggermont, J., and Moore, J. (2012). "Morphological and functional development of the auditory nervous system," in *Human Auditory Development*. Edited by L. Werner, R. Fay, and A.N. Popper (New York: Springer), pp. 61-105.
- Fortnum, H.M., and Marshall, D.H., and Summerfield, A.Q. (2002). "Epidemiology of the UK population of hearing-impaired children, including characteristics of those with and without cochlear implants – audiology, aetiology, comorbidity and affluence," *Int. J. Audiol.*, **41**, 170-179.
- Geers, A.E. (2006). "Factors influencing spoken language outcomes in children following early cochlear implantation," *Adv. Oto-Rhino-Laryng.*, **64**, 50-65.
- Gilley, P., Sharma, A., Dorman, M., and Martin, K. (2006). "Abnormalities in central auditory maturation in children with language-based learning problems," *Clin. Neurophysiol.*, **117**, 1949-1956.
- Golding, M., Pearce, W., Seymour, J., Cooper, A., Ching, T., and Dillon, H. (2007). "The relationship between obligatory cortical auditory evoked potentials (CAEPs) and functional measures in young infants," *J. Am. Acad. Audiol.*, **18**, 117-125.
- Huttenlocher, P., and Dabholkar, A. (1997). "Regional differences in synaptogenesis in human cerebral cortex," *J. Comp. Neurol.*, **387**, 167-178.



- Kang, E., Lee, D., Lee, J., Kang, H., Hwang, C., Oh, S., and Zilles, K. (2003). "Developmental hemispheric asymmetry of interregional metabolic correlation of the auditory cortex in deaf subjects," *NeuroImage*, **19**, 777-783.
- Kral, A., Hartmann, R., Tillein, J., Heid, S., and Klinke, R. (2000). "Congenital auditory deprivation reduces synaptic activity within the auditory cortex in a layer-specific manner," *Cereb. Cortex*, **10**, 714-726.
- Kral, A., Hartmann, R., Tillein, J., Heid, S., and Klinke, R. (2001). "Delayed maturation and sensitive periods in the auditory cortex," *Audiol. Neuro-Otol.*, **6**, 346-362.
- Kral, A., Hartmann, R., Tillein, J., Heid, S., and Klinke, R. (2002). "Hearing after congenital deafness: central auditory plasticity and sensory deprivation," *Cereb. Cortex*, **12**, 797-807.
- Kral, A., Tillein, J., Heid, S., Hartmann, R., and Klinke, R. (2005). "Postnatal cortical development in congenital auditory deprivation," *Cereb. Cortex*, **15**, 552-562.
- Kral A., Tillein J., Heid S., and Klinke R. (2006). "Cochlear implants: cortical plasticity in congenital deprivation," *Prog. Brain Res.*, **157**, 283-313.
- Kral, A., and Eggermont, J. (2007). "What's to lose and what's to learn: development under auditory deprivation, cochlear implants and limits of cortical plasticity," *Brain Res. Rev.*, **56**, 259-269.
- Kral, A., and Sharma, A. (2012). "Developmental neuroplasticity after cochlear implantation," *Trends Neurosci.*, **35**, 111-122.
- Lee, J.S., Lee, D.H., Oh, S.H., Kim, C.S., Kim, J.-W., Hwang, C.H., Koo, J., Kang, E., Chung, J.-K., and Lee, M.C. (2003). "PET evidence of neuroplasticity in adult auditory cortex of postlingual deafness," *J. Nucl. Med.*, **44**, 1435-1439.
- Liegeois-Chauvel, C., Musolino, A., Badier, J., Marquis, P., and Chauvel, P. (1994). "Evoked potentials recorded from the auditory cortex in man: Evaluation and topography of the middle latency components," *Electroen. Clin. Neuro.*, **92**, 204-214.
- Meredith, M., Keniston, L., and Allman, B. (2012). "Multisensory dysfunction accompanies crossmodal plasticity following adult hearing impairment," *Neuroscience*, **214**, 136-148.
- Nishimura, H., Hashikawa, K., Doi, K., Iwaki, T., Watanabe, Y., Kusuoka, H., and Kubo, T. (1999). "Sign language 'heard' in the auditory cortex," *Nature*, **397**, 116.
- Pearce, W., Golding, M., and Dillon, H. (2007). "Cortical auditory evoked potentials in the assessment of auditory neuropathy: two cases," *J. Am. Acad. Audiol.*, **18**, 380-390.
- Ponton, C., Eggermont, J.J., Kwong, B., and Don, M. (2000a). "Maturation of human central auditory system activity: Evidence from multi-channel evoked potentials," *Clin. Neurophysiol.*, **111**, 220-236.
- Ponton, C., Eggermont, J., Don, M., Waring, M., Kwong, B., Cunningham, J., and Trautwein, P. (2000b). "Maturation of the mismatch negativity: Effects of profound deafness and cochlear implant use," *Audiol. Neuro-Otol.*, **5**, 167-185.

- Rance, G., Cone-Wesson, B., Wunerlich, J., and Dowell, R. (2002). "Speech perception and cortical event related potentials in children with auditory neuropathy," *Ear Hearing*, **23**, 239-253.
- Sharma, A., Kraus, N., McGee, T., and Nicol, T., 1997. "Developmental changes in P1 & N1 auditory responses elicited by consonant-vowel syllables." *Clin. Neurophysiol.* **104**, 540-545.
- Sharma, A., Dorman, M., and Spahr, A. (2002a). "A sensitive period for the development of the central auditory system in children with cochlear implants: Implications for age of implantation," *Ear Hearing*, **23**, 532-539.
- Sharma A., Dorman M, Spahr A, and Todd N. (2002b). "Early cochlear implantation in children allows normal development of central auditory pathways." *Ann. Oto. Rhinol. Laryn. Suppl.*, **189**, 38-41.
- Sharma, A., Dorman, M., and Kral, A. (2005). "The influence of a sensitive period on central auditory development in children with unilateral and bilateral cochlear implants," *Hear. Res.*, **203**, 134-143.
- Sharma, A., and Dorman, M. (2006). "Central auditory development in children with cochlear implants: clinical implications," *Adv. Oto-Rhino-Laryng.*, **64**, 66-88.
- Sharma, A., Gilley, P.M., Dorman, M.F., and Baldwin, R. (2007). "Deprivation-induced cortical reorganization in children with cochlear implants," *Int. J. Audiol.*, **46**, 494-499.
- Sharma, A., Nash, A., and Dorman, M. (2009). "Cortical development, plasticity, and re-organization in children with cochlear implants," *J. Commun. Disord.*, **42**, 272-279.
- Sharma, A., Glick, H., Campbell, J., and Biever, A. (2013). "Central auditory development in children with hearing loss: clinical relevance of the P1 CAEP biomarker in hearing-impaired children with multiple disabilities," *Hear. Balance Commun.*, **11**, 110-120.
- Su, P., Kuan, C., Kaga, K., Sano, M., and Mima, K. (2008). "Myelination progression in language-correlated regions in brain of normal children determined by quantitative MRI assessment," *Int. J. Pediatr. Otorhi.*, **72**, 1751-1763.
- Svirsky, M.A., Teoh, S.-W., and Neuburger, H. (2004). "Development of language and speech perception in congenitally, profoundly deaf children as a function of age at cochlear implantation," *Otol. Neurotol.*, **9**, 224-233.
- Trimble, K., Rosella, L.C., Propst, E., Gordon, K.A., Papaioannou, V., and Papsin, B.C. (2008). "Speech perception outcome in multiply disabled children following cochlear implantation: Investigating a predictive score," *J. Am. Acad. Audiol.*, **19**, 602-611.