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Functional near-infrared spectroscopy for neuroimaging in cochlear implant recipients

Joe Saliba [a], [b], Heather Bortfeld [c], Daniel J. Levitin [d], John S. Oghalai [a], *

[a] *Department of Otolaryngology – Head and Neck Surgery, Stanford University, Stanford, CA 94305, USA*
[b] *Department of Otolaryngology – Head and Neck Surgery, McGill University, 1001 Boul. Decarie, Montreal, QC, Canada*
[c] *Psychological Sciences, University of California-Merced, 5200 North Lake Road, Merced, CA 95343, USA*
[d] *Department of Psychology, McGill University, 1205 Avenue Penfield, H3A 1B1, Montreal, QC, Canada*

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ABSTRACT

Functional neuroimaging can provide insight into the neurobiological factors that contribute to the variations in individual hearing outcomes following cochlear implantation. To date, measuring neural activity within the auditory cortex of cochlear implant (CI) recipients has been challenging, primarily because the use of traditional neuroimaging techniques is limited in people with CIs. Functional near-infrared spectroscopy (fNIRS) is an emerging technology that offers benefits in this population because it is non-invasive, compatible with CI devices, and not subject to electrical artifacts. However, there are important considerations to be made when using fNIRS to maximize the signal to noise ratio and to best identify meaningful cortical responses. This review considers these issues, the current data, and future directions for using fNIRS as a clinical application in individuals with CIs.

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Contents

Abbreviations: BOLD, blood-oxygen level dependent; CI, cochlear implant; CW, continuous wave; EEG, electroencephalography; FD, frequency-domain; fMRI, functional magnetic resonance imaging; fNIRS, functional near-infrared spectroscopy; HbO, Oxygenated hemoglobin; HbR, Deoxygenated hemoglobin; MEG, magnetoencephalography; NIR, near-infrared; PET, positron emission tomography; TD, time-domain; SNR, signal-to-noise ratio; SRT, speech reception threshold

* Corresponding author. Department of Otolaryngology – Head and Neck Surgery, Stanford University, 300 Pasteur Drive, Edwards Building, R113, Stanford, CA 94305-5739, USA.

E-mail address: joghalai@stanford.edu (J.S. Oghalai).

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1. Introduction

Cochlear implants (CI) have restored hearing to over 90,000 individuals in the United States in the past 30 years (FDA, 2015). Significant advances in speech processor design, signal processing and surgical techniques have resulted in progressively enhanced performance (Rubinstein, 2004; Roland et al., 2006; Srinivasan et al., 2013). As a result, cochlear implantation has become a highly successful prosthetic solution to replace the function of a sensory organ. Intervention with deaf children has been particularly successful: many children who would otherwise have been placed in schools for the deaf and taught sign language are now learning alongside mainstream peers in a regular classroom environment. The primary goal of cochlear implantation is now open-set auditory-only speech understanding in everyday listening environments. However, while the majority of implant recipients achieve this goal, many still perform poorly (Lazard et al., 2012; Miyamoto et al., 1994).

The factors that contribute to the wide variations in individual outcomes following cochlear implantation are diverse and not completely understood (Lazard et al., 2014; Peterson et al., 2010). Numerous reports have identified age of implantation as a strong predictor of better CI outcome (e.g., the younger, the better) (Kirk et al., 2002; Nikolopoulos et al., 1999; Robinshaw, 1995). Investigators have also demonstrated that children who communicate orally achieve better speech perception skills than children who use visual sign communication (Osberger and Fisher, 2000; Geers et al., 2003). Finally, family income predicted language outcomes in pediatric CI recipients (Holt and Svirsky, 2008). In order to more fully understand how such neurobiological, cognitive, and societal factors influence language outcomes post-implantation, it may be beneficial to examine the neural processing during the perception of auditory stimuli through a cochlear implant. Together with behavioral measures, neurophysiological indicators have the potential to guide post-implant programming in support of deaf patients' speech and language outcomes and, eventually, even predict results for an individual CI patient before implantation occurs.

Functional near-infrared spectroscopy has already been shown to be a reliable neuroimaging modality in both adult and pediatric populations (Fava et al., 2014a,b; Giraud et al., 2001; Quaresima et al., 2012; Wilcox et al., 2005). Generally, reviews of this literature have focused on the use of fNIRS in research on language development and language processing in healthy populations (Crosson et al., 2010; Elwell and C. E. Cooper, 2011; Gervain et al., 2011; Lloyd-Fox et al., 2010; Quaresima et al., 2012; Fava et al., 2011, 2014a,b; Wilcox et al., 2005). More recently, an emerging body of reviews addresses the imaging instrumentation and methodology, as well as approaches to statistical analysis of fNIRS data (Bandettini, 2009; Piper et al., 2014; Scholkmann et al., 2014; Tak and Ye, 2014). However, most relevant to CI research is the fact that fNIRS is compatible with these devices. This review explores applications and limitations of fNIRS in the CI population, comparing it with traditional neuroimaging methods. We summarize the existing literature on the use of fNIRS in adult and pediatric CI recipients, and conclude by outlining possible directions for future research and clinical applications using this promising imaging technique in the CI population.

2. Neuroimaging options in cochlear implant users

Because auditory perception occurs within and beyond the auditory cortex, neuroimaging has the potential to provide an additional clinical measure for assessing whether the electrical stimulation of the cochlea by the CI is reaching and stimulating auditory-specific cortical regions of the brain similar to normal-hearing subjects (Pasley et al., 2012; Steinschneider et al., 2014). Such information can supplement behavioral tests, which are often limited in young CI users (Choi and Oghalai, 2005; Katzenstein et al., 2009; Lin et al., 2010; Oghalai et al., 2009; Santa Maria and Oghalai, 2014; Williamson et al., 2009; Ying et al., 2013). However, there are inherent limitations in the use of all of the currently available neuroimaging modalities in CI recipients, as outlined below and summarized in Table 1.

Functional neuroimaging attempts to identify the brain systems responsible for different behaviors by comparing brain activity during contrasting states (Aine, 1995; Crosson et al., 2010). The logic is that neurons in different areas of the brain associated with specific cognitive processing tasks generate electrical signals when they are active. As a result of this activation, the metabolic needs of neurons change: increased oxygen demand results in increased cerebral blood flow and thus oxygen delivery to that area, with a consequent decrease in deoxygenated hemoglobin (HbR) (Babiloni et al., 2009). Certain neuroimaging modalities, such as EEG, measure this neural activation directly by recording the average electric field potential at different regions of the scalp. In contrast, metabolic neuroimaging methods, such as fMRI, PET, and fNIRS, are indirect, surrogate measures of neuronal activity (Castañeda-Villa

Table 1
Characteristics of the functional neuroimaging techniques currently available for research involving cochlear implant users. See explanations in text, Sections 2.1–2.3.

Technique	Spatial resolution	Temporal resolution	Cochlear implant compatibility	Flexibility in auditory stimuli paradigm	Potential for use in infants	Comments
fNIRS	+ + +	+ + +	Yes	Yes	Yes	
fMRI	+ + + + +	+ +	No*	No**	No	* Structural imaging possible ** Loud background noise
PET	+ + + +	+	Yes	No*	No	* Limited to block design paradigms
EEG	+	+ + + + +	Yes	No*	Yes	*Limited to sound bursts/clicks
MEG	+ +	+ + + + +	No*	No**	Yes	* Requires use of magnet-less implant and simultaneous radio frequency head shield ** Limited to sound bursts/clicks

fNIRS: functional near-infrared spectroscopy, fMRI: functional magnetic resonance imaging, PET: position emission tomography, EEG: electroencephalography, MEG: magnetoencephalography.