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Twenty years of functional near-infrared spectroscopy: introduction for the special issue

David A. Boas [a], Clare E. Elwell [b], Marco Ferrari [c], Gentaro Taga [d]

[a] Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital, Harvard Medical School, USA
[b] Department of Medical Physics and Bioengineering, University College London, Gower Street, London WC1E 6BT, UK
[c] Department of Life, Health and Environmental Sciences, University of L'Aquila, L'Aquila, Italy
[d] Graduate School of Education, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

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ABSTRACT

Papers from four different groups were published in 1993 demonstrating the ability of functional near infrared spectroscopy (fNIRS) to non-invasively measure hemoglobin concentration responses to brain function in humans. This special issue commemorates the first 20 years of fNIRS research. The 9 reviews and 49 contributed papers provide a comprehensive survey of the exciting advances driving the field forward and of the myriad of applications that will benefit from fNIRS.

Introduction

Functional Near-Infrared Spectroscopy (fNIRS) is a non-invasive, non-ionizing method for functional monitoring and imaging of brain hemodynamics used to study human healthy brain function and a variety of pathologies (Ferrari and Quaresima, 2012; Scholkmann et al., 2014). Because of the low absorption of hemoglobin beyond 650 nm, near-infrared light is able to propagate several centimeters through tissue, through the scalp and skull, and spectroscopically interrogate the concentrations of oxygenated, de-oxygenated, and total hemoglobin within the brain. When near-infrared light is shone on the scalp and a detector placed a few centimeters away, changes in the amount of diffuse light reaching the detector corresponds to changes in the optical properties of the tissue below and between the source and detector. A portion of the detected light has sampled the brain and thus provides a measure of changes in cerebral hemoglobin concentrations, as revealed by changes in optical absorption. Because of its safety, low-cost, portability, and high temporal resolution, fNIRS has potential for widespread implementation as a research and clinical tool. Moreover, it is particularly suited for populations and measurement procedures for which other imaging modalities are limited. It is easily applicable in infants, children and agitated patients; procedures involving mobility and interactivity; and procedures performed in locations such as the operating room or intensive care unit. Since its first use to measure brain function 20 years ago by four different groups (Chance et al., 1993; Hoshi and Tamura, 1993; Kato et al., 1993; Villringer et al., 1993), it has proved to be an effective tool to study normal brain physiology and its alteration in disease (Ferrari and Quaresima, 2012; Scholkmann et al., 2014). Dominant application areas include behavioral and cognitive development in infants and children (Benavides-Varela et al., 2011; Cristià et al., 2013; Lloyd-Fox et al., 2010; Quaresima et al., 2012), psychiatric conditions (depression and schizophrenia) (Ehlis et al., 2014), epilepsy (Nguyen et al., 2011; Watanabe et al., 2002), and stroke and brain injury (Obrig, 2014).

fNIRS research is rapidly growing; the number of publications has doubled every 3.5 years over the past 20 years, passing 200 per year in 2012 (Fig. 1). This growth reflects the increasing number of scientists and clinicians beginning to utilize fNIRS for a broad range of applications. The field has now reached a tipping point, with more and more new users exploring the health science and clinical potential in parallel with accelerating advances in fNIRS technology and signal processing. This special issue commemorates the first 20 years of fNIRS research and provides a broad survey of the active areas of study in the field. The issue is divided into seven sections: Instrumentation, Analysis Methods, Neuro-Development, Perception and Cognition, Motor Control, Psychiatric Disorders, and Neurology and Anesthesia.

Instrumentation

fNIRS measurements of brain activation-induced hemoglobin concentration changes are almost exclusively performed with continuous-wave devices, as reviewed in Scholkmann et al. (2014). These are the

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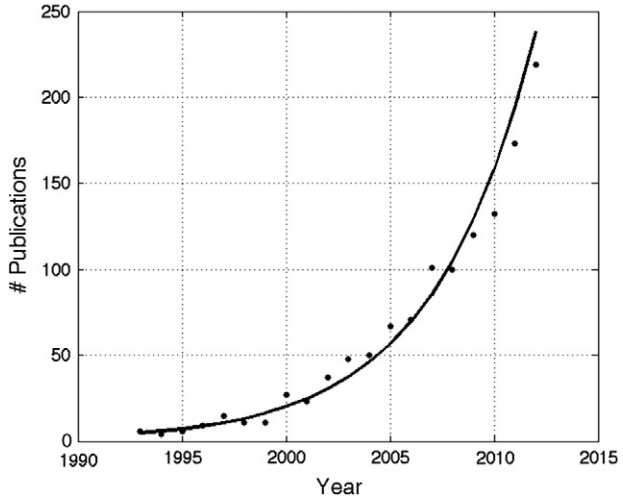

Fig. 1. Number of fNIRS publications per year.

simplest devices, usually utilizing inexpensive laser diodes or even light emitting diodes. These devices measure changes in intensity at different wavelengths, permitting estimation of cerebral hemoglobin concentration changes. Time-domain devices, as reviewed in Torricelli et al. (2014), utilize a short pulse of laser light (usually less than 10s of picoseconds) and measure the temporal broadening of the pulse as it propagates through the tissue. This permits quantification of the baseline hemoglobin concentrations and provides for better spatial resolution and depth discrimination than can be achieved with continuous-wave devices. It is hoped that, with further development, time-domain devices will soon be commercialized for brain activation studies.

Diffuse Correlation Spectroscopy is a close cousin of fNIRS. It can measure relative cerebral blood flow by measuring the decorrelation of the intensity fluctuations in the detected coherent light that is induced by moving red blood cells. This technology is reviewed in Durduran and Yodh (2014) and, when combined with fNIRS, makes it possible to estimate relative cerebral oxygen metabolism. The potential portability of fNIRS is being advanced with wearable fNIRS devices that enable measurement of brain activity during everyday activities, as presented in Piper et al. (2014).

Analysis methods

This section starts with an extensive review of the statistical analysis of fNIRS data, including group analysis using a general linear mixed model within the restricted maximum likelihood framework (Tak and Ye, 2014). The review also discusses filtering of confounding physiological signals and analysis methods for performing resting state functional connectivity studies. The issue of filtering confounding physiological signals arises because fNIRS is generally significantly more sensitive to the scalp than to the brain, particularly in adults. Thus, natural hemodynamic variability in the scalp can obscure brain activation signals. The magnitude of this effect is explored in Strangman et al. (2014) and Funane et al. (2014), while Gagnon et al. (2014) elaborate upon the optimal use of short-separation measurements to filter the confounding signal while simultaneously estimating the brain activation signal. Hassanpour et al. (2014) discuss the extension of statistical analysis methods to the case of high-density measurements that permit image reconstruction of brain activation with improved spatial resolution.

The second comprehensive review in this section, by Tsuzuki and Dan (2014), covers spatial registration methods for fNIRS to assist in anatomical interpretation of the data. The methods described in this review are critical for ensuring that measurements across subjects, groups, studies, and laboratories can be compared within standard stereotaxic space and anatomical labeling. An important component of this registration is the relation between standard 10–20 scalp coordinates and brain coordinates. Analysis of high-density measurements is advancing in parallel and permitting image reconstruction of the brain activation directly on the cortical surface of the subject's true anatomy provided by MRI or on an atlas anatomy, as explored in Ferradal et al. (2014) and Tian and Liu (2014).

Motion artifacts are a common problem for measurements in non-cooperative subjects or studies that involve mobility or movement of the head. Brigadoi et al. (2014) explore the utility of various motion correction algorithms for facilitating the analysis of data otherwise lost to motion artifacts. Yücel et al. (2014) introduce “glue-on” fiber optic probes that employ the same collodion glue used in clinical EEG studies and greatly reduce the magnitude of motion artifacts, permitting measurements of the hemodynamic response to epileptic seizures.

The final five papers in this section investigate the physiological interpretation of fNIRS measurements. Alderliesten et al. (2014) examines the correlation of fNIRS measurements with BOLD fMRI and finds strong correlations between hemoglobin oxygen saturation and BOLD. Fantini (2014) and Pierro et al. (2014) develop and utilize a model of oxygen delivery and consumption that defines a coherent relation of the hemodynamic parameters and permits investigation of cerebral autoregulation and oscillations arising from periodic physiological manipulations. Kolyva et al. (2014) reminds us that fNIRS can also measure cytochrome c oxidase and that this parameter shows greater brain specificity in response to changes in oxygen delivery than the hemoglobin concentrations: an important result that can impact clinical applications of fNIRS. Finally, (Chiarelli et al. (2014) presents exciting new results on measuring the fast optical signal on a time scale of 100 ms, which is more directly related to neuronal activity than the hemodynamic response.

Neuro-development

With respect to applications of the technology, the use of fNIRS techniques to investigate the developing brain is one of the largest growth areas of the past decade. This is due to a combination of factors, including:

- the non-invasive and portable nature of the instrumentation, making it suitable for studies in clinical units and neurodevelopmental psychology laboratories
- technical advances in the design of optical arrays enabling interrogation of multiple brain regions in newborns, infants and children and
- the ability to report on a range of measures relating to neurovascular coupling that may have particular significance in characterizing typical and atypical brain development.

Each of the ten neurodevelopment papers included in this special issue demonstrates how these features are allowing fNIRS to provide new insights into the developing brain over a wide range of ages, from preterm infants to 13-year-olds.

Vanderwert and Nelson (2014) review the current literature in this area, with a particular focus on the role of fNIRS in elucidating our understanding of atypical development, particularly in Attention Deficit Hyperactivity Disorder (ADHD) and autism. Fekete et al. (2014) also focus on atypical development, describing the possibility of using effort control studies in 3- to 5-year-olds to assess the risk of developmental psychopathology. Buss et al. (2014) report on the use of fNIRS in similarly aged children to detect task-specific variations in the frontal-parietal network that underlie visual working memory abilities. An asymptote in the amplitude of the neural signal at the visual working memory capacity limit observed in adults was absent in their data, suggesting that this may emerge sometime after the age of 4 years.

Comparison of neuroimaging data with behavioral or other assessments is an important step in consolidating the role of fNIRS as a useful tool in neurodevelopment studies. Perlman et al. (2014) report evidence of middle and lateral prefrontal cortex (PFC) activity related to