Optics Communications 364 (2016) 93–100

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Diffuse optical tomography based on multiple access coding

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ARTICLE INFO

Article history:
Received 20 April 2015
Received in revised form
4 November 2015
Accepted 6 November 2015
Available online 21 November 2015

Keywords:
Diffuse optical tomography
Multiple access coding
Data acquisition
Simultaneous illumination

ABSTRACT

Diffuse optical tomography (DOT) has the advantages of being a non-invasive, non-radiation emitting and low-cost biological tissue imaging method, and many recent studies have employed this technology. By improving the spatial resolution and developing a new method for constantly improving the flexibility of the experimental device, the system can perform data acquisition rapidly and conveniently. We propose a method for rapid data acquisition based on multiple access coding; it can acquire data in parallel, and the system can greatly improve the temporal resolution of the data acquisition step in diffuse optical tomography thereafter. We simulate the encoding and decoding process of the source–detector pair and successfully isolate the source signal from mixed signals. The DOT image reconstruction highlight the effectiveness of the system.

1. Introduction

During the past 20 years, diffuse optical tomography with near-infrared by virtue of it being non-invasive, non-radiation-emitting and low-cost, has developed rapidly for functional brain imaging. In early 1993 [1,2], DOT was used to measure the hemodynamic response to brain activation, often using a single source–detector pair for data acquisition with a long data acquisition time and low spatial resolution. Maki [3] proposed a multiple channel measure method using 4 sources and 4 detectors for data acquisition with 10 channels; these researchers employed dual wavelength sources with a modulating frequency to divide the multiplexing such that the system can simultaneously measure at the same point, but it did not code the source–detector pair when every source should illuminate sequentially, and the detector only received data from the near source. In 1996, Watanabe [4] employed 10 channels for data measurement with a temporal resolution of data acquisition of 1–2 s. In 1998, Chance presented a fast imaging method using phase modulation with 9 sources and 4 detectors, which required 30 s to acquire one image [5]. In 2000, Franceschini [6] employed 16 sources and 2 detectors with a 32 channels measurement system using back-projection imaging. Every source illuminated sequentially, and the image reconstruction time only required 10 ms; the entire process only required 160 ms. In most multiple channel measurement systems, the measurement data were attained by the interpolation of the sample data or by back-projection for image reconstruction. Although the speed of image reconstruction is rapid, the spatial resolution is comparable to the source detector separation and the quantitative accuracy is compromised in the DOT system.

In the following study, to improve the spatial resolution of DOT, many researchers proposed to arrange more sources and detectors in a measurement system. In 2002, Yamamoto [7] analysed the influence of spatial resolution specifically on different arrangements of optical fibres. These researchers revealed 3 types of arranged optical fibres including, lattice arrangement (LA), double density arrangement (DA) and quadruple density arrangement (QA). In the same detection area, the greater the amount of optical fibre, the more sampling data obtained, the less distance between the source–detector pair and the spatial resolution correspondingly increases. Due to the increase in the optical fibre (channels), there is a greater requirement for data acquisition times. The primary cause of this long data acquisition period is that the sources cannot illuminate simultaneously, and only one source can illuminate at the same time. While many sources illuminate simultaneously, it means that multiple signals must transmit to the detector, but the detector cannot distinguish mixed signals; therefore, it is unable to reconstruct the image. If we can isolate the mixed signal from the detector, then all sources can illuminate simultaneously and the time of data acquisition will be notably reduced. Boas [8] in 2004 and Joseph [9] in 2006 considered the nearest and second-nearest-neighbour source–detector pair for overlapping measurements and presented frequency encoding with time-division multiplexing. This approach requires a large dynamic range, particularly to support overlapping measurements

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http://dx.doi.org/10.1016/j.optcom.2015.11.012
0030-4018/

in which a detector may be required to measure signals from nearby and far sources simultaneously. The researchers used 8 sources which were divided into 3 groups with frequency encoding of the sources. One time interval can illuminate one group, which requires enough distance between sources and a large dynamic range. However, it cannot illuminate all sources simultaneously. Culver's team presented high-density DOT [11–14]; it can detect the four nearest distances (first-, second-, third-, and fourth-nearest-neighbour pairs) for data acquisition. 24 sources were encoded (frequency-, time-, and spatial encoding), two wavelengths at each source position were modulated at different frequencies, and the source positions are time-encoded. The first and last 12 source positions are separated sufficiently in space such that that they can be illuminated simultaneously with different frequency encoding. In 2014 [15,16], they used 92 sources and time-encoded the sources for different groups; however, data acquisition was relatively complicated.

Hence, the greater the sources, the more sophisticated the data acquisition and the longer the data acquisition time. Although this property can be changed by encoding and arranging the optical fibre, it cannot essentially change the complex of the data acquisition system. In the data acquisition complex for DOT, now every source has to illuminate sequentially or a few sources must illuminate at the same time with specific requirements for distance and dynamic range. If all sources can illuminate simultaneously, transmit the signal to the detector concurrently, and isolate the mixed signal, then the data acquisition system will be simple, and the temporal resolution of the attained data will be highly improved.

In the near-infra-red DOT research, image reconstruction requires multiple sources in different positions with different detectors, which requires an increase in the number of source–detector pairs. The detector will receive many source signals, and every source–detector pair is required to acquire data respectively. Thus, the data acquisition time of the whole image will be increased along with more source–detector pairs. In previous research on DOT, many scholars proposed methods to improve the situation, such as time-division multiplexing of multi-channels, which uses an optical switch to control and illuminate each source–detector pair sequentially. In the literature [9,10], Joseph and Barbour encoded the source with frequency encoding combined with time-division multiplexing. The oscillator produced different frequencies of a fixed wavelength source, and multiple sources can transmit at the same time to the detector. Because of the different signal frequencies that do not interfere, it can distinguish the signal from mixed data. The time-division multiplexing method uses an optical switch which is controlled by the computer, but it cannot shorten the time. Frequency encoding can illuminate simultaneously, but it changes the source properties. If we do not change the source properties and illuminate simultaneously when the detector receives a signal at the same time, then we can acquire data rapidly without changing the system. We proposed a method based on orthogonal encoding for data acquisition that can illuminate all sources simultaneously and isolate a single value for each source illumination alone from the mixed detected data.

2. Multiple Access Code for DOT

The traditional data acquisition stage for the experimental system is shown in Fig. 1(a), including the source fibre, tissue detection, detection optical fibre and data receiving device. ①$1 \times N$ source switch of the time-division multiplex, ②N source optical fibres, ③detected tissue that has inclusion (cuboid phantom has a cylindrical inclusion), ④filter used to filter the received data to eliminate signals such as noise, ⑤detection optical fibre, ⑥PMT (photomultiplier tubes) used for photoelectric conversion and to amplify the signal. In addition to the time-division multiplex method, certain methods use frequency encoding. We present a method shown in Fig. 1(b) which can change the conditions of the time-division multiplex, illuminate the parallel sources and receive parallel data, as well. ①The optical encoder used to encode the N sources optical fibre, ②N encoded sources optical fibres not using the optical switch, ③the same detected tissue, ④M detection optical fibres, ⑤the optical fibre decoder used to isolate the mixed data, ⑥and APD arrays used to receive the detected data. The experimental system that we present is simpler and faster than previous systems.

The difference between our method and the conventional method is the source of the optical fibre. We encoded all of the source optical fibres, illuminated all sources simultaneously, and detected the mixed data in parallel and then isolated each single value by the decoder. Finally, the APD arrays receive the separated data for image reconstruction. Image reconstruction requires the data from every illuminated source; therefore, we need to isolate the data from the mixed signal, which is key for decoding the encoded value of the sources.

In the signal transmission, provided that the channel bandwidth is B based on the Shannon's theorems [16], the channel capacity theoretical equation is $C = B\ \log_2(1 + S/N)$, where C is the channel capacity (bit/s); B is channel bandwidth (Hz); S is the signal average power and N is the noise average power. If we want to enlarge the information transmission rate, we must enlarge the channel bandwidth B or the signal to noise ratio S/N. With the fixed S/N, in order to transmit more information, we must increase the bandwidth B. In the DOT system, the optical fibre is mainly used to transmit the signal; the bandwidth of the optical fibre is notably wide and can theoretically reach an infinite amount.

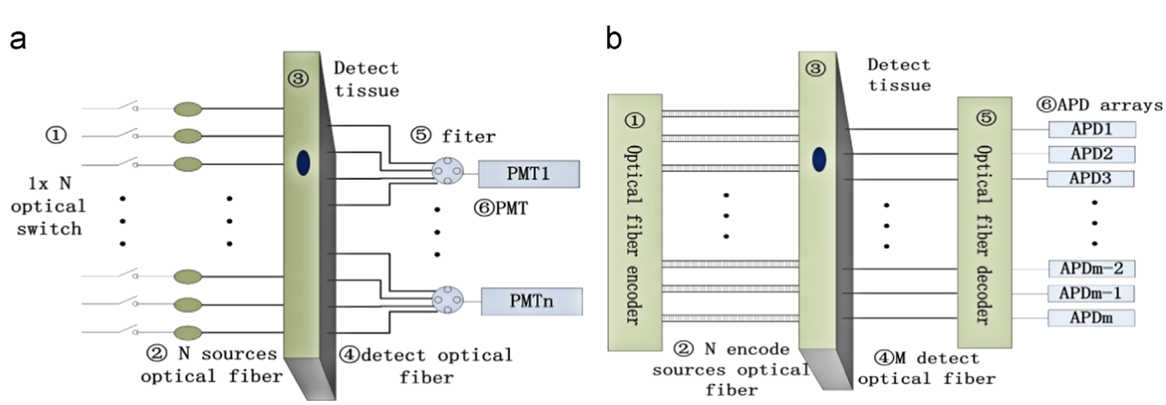

Fig. 1. Experiment device of data acquisition stage. (a) The time-division multiplexing way (b) parallel detect way presented in the paper.