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Optical Property Measurements in Normal Human Brain Tissues: Exploring Discrepancies in the Visible-NIR Region

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ABSTRACT

This paper highlights the various factors that contribute to scattering coefficient variations within human brain tissues and theoretical penetration depth. These are critical parameters for biomedical applications and neuroscience research. Brain tissue's complex nature, experimental technique variability, tissue composition and structure, tissue type, sample preparation, and temperature all potentially impact optical measurement accuracy and reliability in brain tissue research. Understanding and minimizing these sources of error is crucial for improving data quality and interpretation in biomedical applications. This study identifies the main sources of variation and vast range of optical values, such as the scattering coefficient, for the human brain. This article presents a comprehensive analysis of the optical properties of normal human brain tissues within the wavelength range of 600 nm to 900 nm, combining our original findings with existing literature reviews. Consequently, this work aims to enhance the reliability and consistency of measurements as well as determine the theoretical penetration depth for future imaging of the human brain.

Ultimately, this can help advance current knowledge regarding human brain tissues and aid in the diagnosis and treatment of brain-related disorders. Scattering properties differ between the gray and white matter regions of the human brain, and this has implications for imaging and diagnostic techniques in neuroscience. The attenuation coefficient, which is calculated using absorption spectra from normal gray matter of the human cerebral cortex (10.9–14.7 mm^{-1}), provides valuable insight into gray matter optical properties. The calculated penetration depth within the 600–900 nm wavelength range is between 1.8 and 8.7 mm, representing the theoretical limit for imaging deep into human brain tissues.

Keywords: Optical properties; Scattering Coefficient; Brain Tissues; Optical Imaging; Diffuse Reflectance Spectroscopy; Optical Coherent Tomography; Confocal Microscopy; Light Scattering

Abbreviations: VIS-NIR: Visible-to-Near Infrared; OCT: Optical Coherence Tomography; NDRI: National Disease Research Interchange; UV-VIS: Ultraviolet-to-Visible

Introduction

Noninvasive measurements of human brain tissues using various spectroscopic and optical imaging techniques within the visible-to-near infrared (VIS-NIR) region play a crucial role in advancing our understanding of brain function and pathology [1]. These noninvasive methods enable researchers and clinicians to obtain valuable information regarding tissue composition, oxygenation levels, temperature, and structural changes without the need for invasive procedures [2-5]. Such noninvasive measurements hold significant potential for application in neuroimaging, diagnostics, and monitoring brain health. They offer a safer and more accessible means of examining the brain in both clinical practice and advancements in neuroscience research. The human cerebral cortex comprises gray and white matter, each with distinct characteristics and functions [6,7]. Gray matter, found on the outer layer, consists of neuronal cell bodies, dendrites, glial cells, and synapses, and it is crucial for information processing and higher-order brain functions. In contrast, white matter, located beneath gray matter, primarily comprises myelinated axons that form neural pathways, and it facilitates signal transmission and interregional communication. Gray matter is denser, with concentrated cellular components, while white matter occupies a larger volume and is characterized by myelinated axonal fibers.

Brain tissue's optical properties, such as the scattering coefficient, scattering length, and g value, are critical parameters for several biomedical applications and neuroscience research, including spectroscopy and optical imaging. The scattering coefficient represents the probability of light being scattered per unit length, while the scattering length describes the average distance that light travels before being scattered. The g value represents the anisotropy of scattering, which describes the angular distribution of scattered light. However, measuring these properties accurately is potentially challenging because of the complex nature of brain tissue and variety of measurement techniques available. However, discrepancies in optical property measurements emanating from different techniques have been reported [8-18]. This discrepancy can have significant implications on the interpretation of results and accuracy of conclusions drawn from them. Understanding the sources of discrepancy and developing strategies to address them is crucial for advancing our understanding of brain tissues using optical techniques. "What causes this wide range of differences?" In this study, we perform a comparative analysis of different techniques used to measure the optical properties of brain tissue, including diffuse reflectance spectroscopy, optical coherence tomography (OCT), confocal microscopy, time-resolved spectroscopy, and light scattering spectroscopy [8-18]. We explore the factors contributing to discrepancies in the optical property measurements of brain tissues when using different techniques and discuss strategies for minimizing these discrepancies. Our findings will provide insight into the factors that potentially affect the accuracy and precision of optical property measurements in brain tissue and guide researchers towards more reliable and consistent measurements.

Based on the available literature, scattering coefficient values can be categorized into two distinct regions, as outlined in Table 1. Notably, certain publications do not explicitly specify the specific brain tissue region being considered, such as gray or white matter, whereas others do (Table 1) shows the range of optical properties of human brain tissues measured using OCT, confocal microscopy, time-resolved spectroscopy, and light scattering techniques in the 600–900 nm VIS-NIR region based on reviewed literature. According to the literature, the anisotropy factor g for human brain tissues generally lies within the 0.86–0.94 range at wavelengths between 600 and 900 nm [19,20]. Other publications not included in this table may contain different or more specific values for these optical properties. The scattering length (ls), which is the inverse of the scattering coefficient (μs), can be determined as shown in (Table 1).

Table 1: Literature review-based scattering coefficient and scattering length ranges using different techniques for examining human brain tissues.

Scattering Coefficient (mm^{-1})	Scattering Length (mm)	Technique Used	Reference
2–20	0.05–0.50	Diffuse Optical Imaging and Tomography, Confocal Microscopy, Time-Resolved Spectroscopy, Light Scattering	[8-18]
20–50	0.02–0.05		

Materials and Methods

Determining the attenuation coefficient is crucial in tissue imaging as it directly influences the critical penetration depth. To accurately calculate this coefficient, an effective approach must entail analyzing absorption spectra obtained using a UV-VIS double-beam spectroscopy system, such as the U-2910 Hitachi Medical System [17]. In the present study, we focused on calculating the attenuation coefficient within the 600–900 nm wavelength range for a specific thickness of human gray matter (300 μm) in the cerebral cortex tissue obtained from the National Disease Research Interchange. By plotting the relationship between wavelength (600–900 nm) and the corre-

sponding attenuation coefficient, we sought to gain valuable insight into the optical properties of gray matter in human cerebral cortex tissue. Furthermore, we aimed to determine the transport length and penetration depth of human brain tissues within the 600–900 nm wavelength range using relevant publications in the literature as our reference. Additionally, we investigated the correlation between scattering coefficient and penetration depth in human brain tissues. This analysis holds significant importance in accurately predicting penetration depth in human brain imaging applications.

Results and Discussion

Highlighting that the scattering coefficient can exhibit variations influenced by multiple factors is imperative. These factors potentially contribute to the observed variability in scattering coefficients within human brain tissues. One significant factor contributing to variations in these properties is the experimental technique used to measure them. The sensitivity and precision of the instruments used to measure optical properties potentially affects the accuracy and reproducibility of the results obtained. Furthermore, discrepancies in the observed optical properties can arise due to inherent variations in tissue composition and structure. These variations may differ among individuals or even within the same person, further influencing the optical characteristics of the tissues [21-24]. Additionally, factors such as tissue age, preservation methods, and pathologies also potentially impact the scattering coefficient. As such, careful consideration of these variation sources is critical when interpreting and comparing data from different studies.

Diffuse optical imaging and tomography techniques may encounter errors arising from the inaccurate placement of optical probes, motion artifacts caused by subject movement, and the impact of light absorption or scattering by superficial layers [25-27]. Their measurements can also be affected by the inaccurate modeling of tissue heterogeneity, limited spatial resolution and depth penetration, and potential errors during the reconstruction of the internal distribution of optical properties. Confocal microscopy measurements are possibly prone to errors caused by misalignment or optical aberrations [28,29]. In addition, signal loss may result from out-of-focus illumination, and sample-induced scattering or refractive index mismatches may occur. Time-resolved spectroscopy measurements are potentially affected by inaccuracies in determining photon flight time, detector noise and dark count rate, and the incomplete modeling of photon migration within tissues [30,31]. Light scattering measurements can be influenced by multiple scattering events, that is, the incomplete removal of scattering contributions from other sources [17,24,32].

In addition, they are sensitive to tissue structural changes or size distribution. Awareness of these possible sources of error is crucial for optimizing experimental setups, data interpretation, and advancing the accuracy and reliability of optical measurements in diverse biomedical applications. Understanding and mitigating these potential sources of error are critical for improving the accuracy and reliability of optical measurements in biomedical research and clinical applications. By addressing these challenges, researchers and practitioners can enhance data quality and interpretation, ultimately leading to more robust and meaningful outcomes in the field of optical imaging. The specific sources of error may vary depending on the implementation method and experimental setup used within each technique. The accuracy and reliability of optical measurements in brain tissue can be influenced by several tissue-related factors. First, sample preparation techniques, such as sample thickness, tissue dehydration, and fixation and slicing, potentially introduce artifacts or alter tissue properties. The selection of a specific brain region for sampling, such as the frontal, parietal, temporal, or occipital lobe, can result in significant differences in tissue composition and optical properties.

Tissue composition encompasses the types and organization of cells, including neurons, glial cells, and blood vessels. This can vary across different brain regions. Similarly, optical properties, such as the anisotropy factor and scattering coefficients, also potentially vary based on the densities and arrangements of these cellular components. Thus, understanding the impact of brain-region selection is essential for investigating optical properties, as it substantially influences the interpretation and generalizability of findings in studies focusing on specific brain areas. Additionally, different types of brain tissue being investigated whether white or gray matter, can exhibit varying scattering and absorption characteristics. Moreover, the temperature at which an experiment is conducted potentially influences tissue properties and alters optical measurements [15,33-36]. Sources of error originating from sample preparation, tissue region, tissue type, and temperature emphasize the requirement for careful consideration and standardization in experimental design. This minimizes error sources and ensure accurate and reliable optical measurements in brain tissue research.

According to the literature, as shown in (Table 1), as well as our own research findings, the scattering coefficient of human gray matter in the cerebral cortex typically falls within the 2–20 mm-1 range. In contrast, white matter exhibits a higher scattering coefficient, exceeding 20 and occasionally reaching values of approximately 50 mm-1 or above. Gray matter has a lower scattering coefficient than white matter. These findings highlight the inherent differences in scattering properties between gray and white matter regions within the human brain. These differences have significant implications for various imaging and diagnostic techniques in neuroscience.

Table 2: Th values for transport length and penetration depth based on (Table 1), assuming an anisotropy factor (g) of 0. 9 and absorption coefficient of 0.02 mm^{-1}.

Scattering Coefficient (mm^-1)	Scattering Length (mm)	Transport Length (mm)	Penetration depth, δ (mm)	Technique Used	Reference
2–20	0.05–0.50	0.5–5	2.9 – 8.7	Diffuse Optical Imaging and Tomography, Confocal Microscopy, Time-Resolved Spectroscopy, Light Scattering	[8-18]
20–50	0.02–0.05	0.2–0.5	1.8–2.9		

(Table 2) presents the range of optical properties observed in human brain tissues, as outlined in (Table 1). Additionally, this table includes the computed values for transport length (lt) using equation 1 and penetration depth (δ) using equation 2. We adopted a value of 0.90 for the anisotropy factor (g) [19,20]. The values in this table correspond to those in the literature between 600 and 900 nm. Equations 1 and 2 are as follows:

$$l_t = \frac{1}{\mu_s(1-g)} = \frac{l_s}{(1-g)}, \qquad (1)$$

$$\delta(\lambda) = \frac{1}{\sqrt{3\mu_a(\lambda)\left(\mu_a(\lambda)+\mu_s(\lambda)(1-g)\right)}}, \qquad (2)$$

where $\mu_a(\lambda)$ is the absorption coefficient. Human brain tissues have an absorption coefficient of approximately 0.02 mm^{-1} between 600 and 900 nm, according to the literature [9,37]. These calculations offer valuable insight into the behavior of light as it propagates through tissues, revealing the maximum distance it can traverse and depth at which it can effectively penetrate to enable noninvasive imaging of neurons in deep tissue regions. The findings presented here provide valuable information regarding the optical properties of gray matter in human brain tissue. The plot in (Figure 1) illustrates the relationship between penetration depth and scattering coefficient from (Table 2) for normal brain tissues within the 600–900 nm wavelength range, as reported in the literature. The penetration depth was determined using Equation 2, considering an anisotropy factor (g) value of 0.9 and absorption coefficient of approximately 0.02 within the same wavelength range. Notably, the absorption coefficient, which remained relatively constant (ranging from 0.01 to 0.03), was significantly smaller than the scattering coefficient in this region.

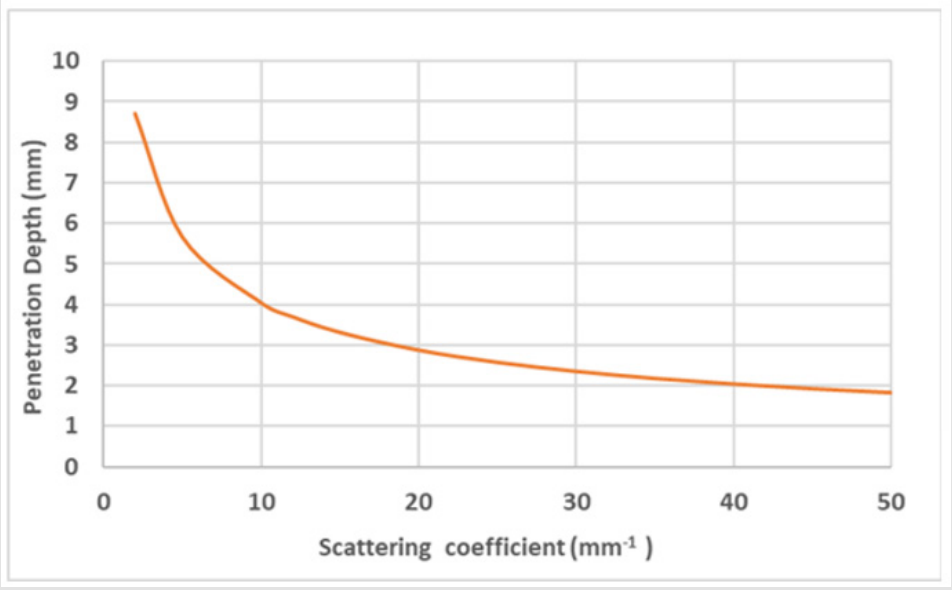

Figure 1: Penetration depths of human brain tissues across the 600–900-nm range according to the literature.

The penetration depth of normal human brain tissue samples varied from 1.8 mm (at a scattering coefficient of 50 mm^{-1}) to 8.7 mm (at a scattering coefficient of 2 mm^{-1}). The penetration depth represents the theoretical limit for imaging deep into human brain tissues. The attenuation coefficient for normal human gray matter, which plays a crucial role in determining the critical depth for tissue imaging, can be calculated from the absorption spectra obtained using a UV-VIS double-beam spectroscopy system, specifically the U-2910 Hitachi Medical System [17]. In this study, we calculated the attenuation coefficient for a specific section (300 μm) of the gray matter in the cerebral cortex of human brain tissue, focusing on a 600–900 nm wavelength range. The attenuation coefficient of gray matter in normal human brain tissue samples, as calculated using a UV-VIS double-beam Hitachi Medical system, ranged from 14.7 mm^{-1} at 600 nm to 10.9 mm^{-1} at 900 nm. The corresponding results provide valuable insight into the optical properties of gray matter in normal human brain tissue and are shown in (Figure 2).

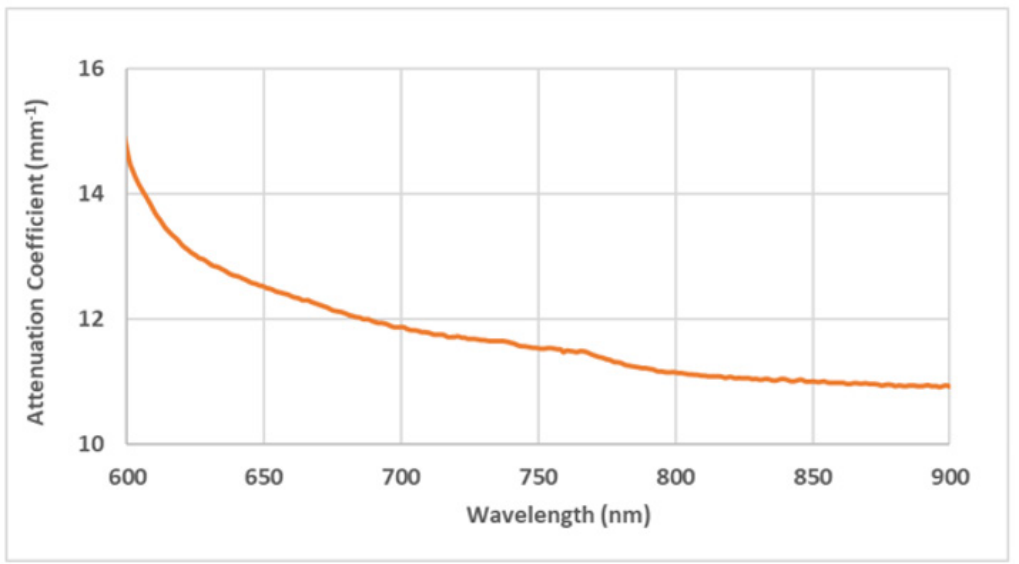

Figure 2: Attenuation coefficient (mm^{-1}) of gray matter in normal human brain tissue, calculated from absorption spectra using a UV-VIS double beam Hitachi Medical System.

Conclusion

In conclusion, the scattering coefficient in human brain tissues is influenced by factors such as experimental technique, placement of optical probes, motion artifacts, sample preparation method, tissue state, tissue composition, and structural variations. It is important for researchers to consider these factors when performing and reporting optical property measurements of brain tissues to ensure the accuracy and reproducibility of their results, advance our understanding of biological tissues, and facilitate meaningful scientific discoveries. This study yielded scattering coefficients ranging from 2 to 20 (mm^{-1}) and exceeding 20 to approximately 50 (mm^{-1}) in the gray and white matter of the human cerebral cortex, respectively. Computed values for transport length and penetration depth based on these scattering coefficients provide valuable insight into the optical properties of normal human brain tissues. In the wavelength range of 600–900 nm, attenuation coefficients and penetration depths were calculated to establish theoretical limits and potential capabilities of imaging human brain tissues within this specific range. The calculated attenuation coefficient for normal human gray matter falls between 2 and 15 mm^{-1}. The calculated penetration depth, ranging from 2 to 9 mm within the 600–900 nm range, represents the theoretical limit of deep penetration into human brain tissues. These findings enhance our knowledge and understanding of the optical properties of the human brain. They have potential implications for enhancing spectral and imaging approaches in the field of neuroscience.

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Conflict of Interest

The authors have no conflict of interest relevant to this study to declare.

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