Application of dynamic light sources produced by unique optics to stimulate the human cerebrum

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Abstract

A light source, which produces many bright spots and can change its number dynamically, was developed two ways. One was with a computer simulation, and the other was an experiment employing a rotating disc with a white-light laser. These light sources were applied to optical stimulation of the human cerebrum, and the strength of the cerebral reaction was measured using optical topography (OT). The primary findings were that, (1) Younger subjects (20's) were most sensitive, followed by middle-aged subjects (50's), and finally senior-aged subjects (60's), (2) Oxygenated hemoglobin exhibited an increasing tendency in response to optical stimulation, whereas deoxygenated hemoglobin showed little changeable tendency, (3) The rotation period of the disk, and thus the flickering speed of the light spots, at $T = 2.4$ s presented stronger stimulation, while stimulation decayed at a longer period $T = 4.8$ s in the case of the experiment, but vice versa with the light source produced by computer simulation.

Key Words

Diffraction, Arago spot, Human cerebrum, Optical topography, Hemoglobin

1. Introduction

Most commonly, the effect of various types of stimulation on the human cerebrum including motor tasks, sound, or visual tasks such as looking at pictures or photographs of landscapes, has been measured quantitatively using optical topography (OT).^{1,2)}

On the other hand, we have a special interest in the dynamic optical stimulation of the human senses. His-

torical research has reported that monkeys prefer blue illumination, and react negatively to red illumination.³⁾ Thus, in our latest work,⁴⁾ we compared three types of stimulation and thereby confirmed how OT performs in the measurement of dynamic optical stimulations compared with stimulations employed in leading research.

In this paper, we distinguish visual stimulation and optical stimulation from the viewpoint of the direction of light, namely, if it comes from the back, it is defined as visual stimulation, while light from the front characterizes optical stimulation. The word "visual task" is relevant to both stimulations.

From a physical point of view, there are many differences in light sources: (1) passive or active, (2) mono or multi color, (3) spontaneous or stimulated emission, (4) stationary or dynamic. Passive light is produced by reflection from pictures or photographs, whereas active light is produced by a natural source, for instance, the

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direct view of fire, lightning, sunset glow and so on. These natural light sources are, however, based on spontaneous emission. Our attention is focused on active and stimulated emissions, namely the laser light which can produce the dynamic light, i.e., the speckled light by its coherence property. Due to our experimental findings that blue laser speckles produced by the Sr^+ recombination laser⁵⁾ or the super broadband color center laser^{6,7)} elicit a peaceful feeling and result in emotional stabilization, we are eager to clarify these findings scientifically and quantitatively by employing OT. Thus, we first made sure that OT was applicable to our research subjects.⁴⁾

With the aim of developing a dynamic light source that is as close to the laser speckle as possible, we attempted to employ a rotating disk. Changing the rotation speed of the disk, we can produce a cyclic change of bright spots which look like shining stars in the night sky. The white light spots in the blue background can be produced by white light lasers.

In this paper, the theory of the mechanism that generates the bright spots, the dividing of the Arago spot, and its simulation are carried out first, then experimental results employing the disc and the white-light laser will be reported, and finally the state of the human cerebrum under the optical stimulation is demonstrated by the distribution map of the hemoglobin by employing OT.

2. Theoretical preparation for simulation and calculated results

We use a transverse coordinate system, as shown in Fig. 1, for calculating the diffracted amplitude distribution of a diffracting object. The diffracting object whose amplitude distribution is presented by $g(\xi, \eta)$ is set on the incident plane at $(\xi, \eta, 0)$, then the diffracted amplitude distribution of the diffracting object on the observation plane (x, y, z) is described within the Fresnel diffraction approximation by

$$U(x, y) = \frac{1}{i\lambda z} \exp\left[ik\left(z + \frac{x^2 + y^2}{2z}\right)\right] \iint g(\xi, \eta) \times \exp\left[ik\frac{\xi^2 + \eta^2}{2z}\right] \exp\left[-i2\pi\left(\frac{x\xi}{\lambda z} + \frac{y\eta}{\lambda z}\right)\right] d\xi d\eta, \quad (1)$$

where k is the wave number and λ is the wavelength. Figure 2 shows circular and elliptical obstacle models for

use in the calculation of diffraction patterns. The circular obstacle is 2 mm in diameter and the elliptical obstacles correspond to the projected figures of the circular obstacle which is rotated 30, 45 and 60 degrees. For simplicity, we define their amplitude distribution functions as

$$g(\xi, \eta) = \begin{cases} 0 & \text{when } (\xi, \eta) \in \text{obstacle} \\ 1 & \text{when } (\xi, \eta) \notin \text{obstacle} \end{cases}. \quad (2)$$

Instead of substituting Eq. (2) into Eq. (1) and evaluating the integral over the entire area except for the obstacle on the incident plane, we calculate the diffracted amplitude distribution of the complementary aperture and apply Babinet's principle to the result to derive the desired diffracted amplitude distribution of the obstacle. According to Babinet's principle in scalar diffraction theory for Fresnel diffraction region,⁸⁾ diffracted amplitude distributions of complementary objects, an obstacle and the complementary aperture, are related by

$$U_o(x, y) + U_A(x, y) = \exp(ikz), \quad (3)$$

where $U_o(x, y)$ and $U_A(x, y)$ are diffracted amplitude distributions on the observation plane corresponding to the obstacle and the complementary aperture. And the function $\exp(ikz)$ represents an incident plane wave along the direction of the z axis. Thus, using Eq. (3), the integral area in Eq. (1) is reduced to only the inside of the complementary aperture. The resultant intensity distribution, namely the diffraction pattern, is expressed by

$$I(x, y) = |U_o(x, y)|^2 = |\exp(ikz) - U_A(x, y)|^2. \quad (4)$$

In the calculation, the wavelength of 633 nm is used.

Fig. 1. Coordinate system for calculation of the diffraction amplitude distribution.

Fig. 2. Circular and elliptical obstacles: (a) a circular obstacle of 2mm in diameter, (b)-(d) elliptical obstacles corresponding to projected figures of the circular obstacle (a) rotated 30, 45 and 60 degrees, respectively.

Fig. 3. Calculated diffraction patterns at $z = 100$ cm: (a) Arago spot in diffraction pattern of a circular obstacle shown in Fig. 2(a), and (b)-(d) diffraction patterns of elliptical obstacles shown in Figs. 2(b), 2(c) and 2(d), respectively.

Figure 3 shows calculated diffraction patterns of the obstacles shown in Fig. 2 at $z = 100$ cm. In Fig. 3(a) a single bright spot, namely the Arago spot, exists at the center of the shadow of the obstacle and concentric circular fringes around the Arago spot appear clearly. Figures 3(b), 3(c) and 3(d) show the diffraction patterns of the elliptical obstacles. As the rotation angle changes from 0 degrees to 60 degrees, the Arago spot and concentric cir-

cular fringes are divided into many bright spots which align parallel to the major axis of the elliptical obstacle.

This dividing phenomenon of the Arago spot and concentric circular fringes is explained as follows. As the rotation angle becomes larger, the elliptic arc in the major axis direction of the obstacle closes to a line parallel to the major axis, and diffracted lights at that elliptic arc make continuous straight fringes. In addition, diffracted lights

at the elliptic arc in the minor axis direction interfere with diffracted lights at the elliptic arc in the major axis direction, which result in many light spots.

3. Experimental method and results

3.1 Division of Arago spot

The optical system employed in the experiment for dividing the Arago spot is illustrated in Fig. 4. The light source is a white-light laser that oscillates the three primary color beams (KOITO Co., Ltd., KLP-330, red: 636.0 and 635.5 nm, green: 537.8 and 533.7 nm and blue: 441.6 nm). Laser beams illuminate an obstacle perpendicularly, and the diffracted light made by the obstacle forms the diffraction pattern onto a CCD camera. In the experiments, a disk 5.6 mm in diameter was used as an obstacle. The disk was located at a distance $z = 100$ cm from the CCD camera, and was rotated to the angles of 0, 30, 45 and 60 degrees around the axis of the diameter. The diffraction patterns recorded by the CCD camera are shown in Fig. 5. Figures 5(a) to 5(d) correspond to the

diffraction pattern at the rotation angle from 0 to 60 degrees, respectively. As already seen in the case of the calculated diffraction patterns in Fig. 3, the Arago spot and concentric circular fringes are also divided into many spots in the experiment similarly by the rotation of the disk. The number of spots produced increases with the increase of the rotation angle.

Fig. 4. Experimental setup for the recording of diffraction patterns. NDF is a neutral density filter, SF is a spatial filter, CL is a collimator lens and O denotes an obstacle, which is a disk of 5.6 mm in diameter.

(a) 0 deg

(b) 30 deg

(c) 45 deg

(d) 60 deg

Fig. 5. Light spots recorded by a CCD camera at $z = 100$ cm: (a) Arago spot in diffraction pattern of a disk, (b)-(d) light spots produced by rotation of a disk.

3.2 Optical topography measurement

The diffraction patterns calculated by computer simulation and obtained by experiment were applied to the optical stimulation of the human cerebrum, and its response to the optical stimulation was measured by OT (Hitachi Ltd., ETG-4000). The diffraction patterns at each rotation angles (0, 15, 30, 45 and 60 degrees) were displayed on a monitor in the order of the rotation angle from 0 to 60 degrees and vice versa, at the time interval of 0.1 s and 0.2 s corresponding to the rotation period of the disk of $T = 2.4$ s and 4.8 s, respectively. Therefore, it corresponds to the flickering period of light spots. The subjects were instructed to look at the animated images of diffraction patterns for 30 s in the task phase and a static image of diffraction pattern at a 0-deg rotation angle for 30 s in the rest phase. The measurement data of OT were averaged over five repetitions of the task-rest cycle.

Figure 6 and Figure 7 represent the OT images. In the case of the young generation, three subjects are listed with differences among them in time dependence, but the cerebral reaction of young generation (20's) is most sensitive, followed by middle-aged generation (50's), then senior-aged generation (60's). On the influence of rotation period of the disk, $T = 2.4$ s gave stronger stimulation with experimental light spots, being decayed at $T = 4.8$ s (see Fig. 6(b)) than that at $T = 2.4$ s (see Fig. 6(a)). On the other hand, $T = 4.8$ s gave stronger stimulation with computer simulation light spots (see Fig. 7(a)), being decayed at $T = 2.4$ s (see Fig. 7(b)). Figures 8 and 9 represent the data of deoxygenated hemoglobin. Both the experiment and computer simulation resulted in less notable results. From these, the concentration of oxygenated hemoglobin exhibited an increasing tendency in response to the optical stimulation, whereas, that of deoxygenated hemoglobin was not recognizable.

4. Discussion

4.1 Production of light source

The phenomenon of division of an Arago spot into many small bright spots by rotation of a circular obstacle such as a disk, has been reproduced by computer simulation. In the case of computer simulation, the light spots appearing on the display are white, active, and flickering, but they are based on spontaneous emission. On the other hand, in the case of an experiment with a disk and white-light laser, the light spots produced are stimulated emission. However, once we store the data with a CCD camera and display it on the computer screen, it is no

longer stimulated emission, but spontaneous emission.

A few differences have been noted between calculated results and experimental ones as far as we look at the display. We consider that those would be caused by the difference in wavelength as well as diameter of an obstacle employed in computer simulation. In computer simulation, white light spots consist of a single spectrum of 633 nm, whereas there are three primary colors in the experiment. However, we can produce a light source that looks like shining stars in the night sky in both computer simulation and experimental ways.

4.2 Optical topography measurement

Our aim is to apply these light sources to induce dynamic optical stimulation in the human cerebrum from the point of view providing comfortable surroundings to the subjects.

The reaction of the human cerebrum is confirmed using OT. The probe sheet covers the frontal lobe as well as both side lobes. Thus, we can obtain information on the hemoglobin distribution at three positions. Figures 6 and 7 show the distribution map of oxygenated hemoglobin. The deeper the red color, the larger is the increase of hemoglobin, and vice versa in the case of blue color. Due to the data processing condition, each map contains the distribution data at the frontal lobe in the center position, but we can also see the activated state of both side lobes at left and right ends of the map, although those are compressed spatially.

From these maps, it is recognizable that the reaction of the cerebrum is most sensitive in younger subjects (20's), followed by middle-aged subjects (50's), and finally senior-aged subjects (60's). Another result concerns the flickering period of the light spots, which are regulated by the rotation speed of the disk. The increase of oxygenated hemoglobin was notable at the rotation period of $T = 2.4$ s in the experiment (see Fig. 6(b)), while it reacted strongly at the rotation period of $T = 4.8$ s in computer simulation (see Fig. 7(a)).

Figures 8 and 9 show the distribution map of deoxygenated hemoglobin. Comparing these figures with those of oxygenated hemoglobin described above (Fig. 6, Fig. 7), the change of hemoglobin distribution is not notable.

Thus, the stimulating effect of active, spontaneous, but dynamic light source appears to increase the concentration of oxygenated hemoglobin, which can promote the cell activity. We are expecting that such optical stimulation

Fig. 6. Mapping of oxygenated hemoglobin distribution stimulated by light spots produced by the experiment; (a) rotation period $T = 4.8$ s, (b) $T = 2.4$ s.

Fig. 7. Mapping of oxygenated hemoglobin distribution stimulated by diffraction patterns produced by computer simulation; (a) rotation period $T = 4.8$ s, (b) $T = 2.4$ s.

Fig. 8. Mapping of deoxygenated hemoglobin distribution stimulated by light spots produced by the experiment; (a) rotation period $T=4.8$ s, (b) $T=2.4$ s

Fig. 9. Mapping of deoxygenated hemoglobin distribution stimulated by diffraction patterns produced by computer simulation; (a) rotation period $T = 4.8$ s, (b) $T = 2.4$ s.

affects the promotion of the neuro-transmitter supply in the human nerve system, and results in a chain reaction which excites human congenital immunology, and finally reaches the strengthening of the self guard and recovery systems in the human body.

5. Conclusion

A dynamic light source that can change the number of bright spots cyclically was produced by computer simulation as well as through an experiment. These light sources were applied to induce dynamic optical stimulation of the human cerebrum, and the strength of the cerebral reaction was demonstrated by color depth in the hemoglobin distribution map obtained using OT.

The primary findings obtained by this research are summarized as follows.

- (1) Younger subjects (20's) are most sensitive, followed by middle-aged subjects (50's), and finally senior-aged subjects (60's),
- (2) Oxygenated hemoglobin exhibited an increasing tendency in response to optical stimulation, while deoxygenated hemoglobin showed little changeable tendency,
- (3) The rotation period of the disk, and thus the flickering speed of the light spots, at $T = 2.4$ s presented stronger stimulation, while stimulation decayed at a longer period $T = 4.8$ s in the case of the experiment, but vice versa with the light source produced by computer simulation.

Detailed experiments and analysis on the effect of a dynamic optical stimulation to the human cerebrum, and preparation of a comfortable environment for the human mental state by employing an active light based on stimulated emission, are now under way. Our scenario of psychiatric healing is standing on an acting route from blue laser speckle to the promotion of neuro-transmitter transportation, and thereby to excite the active immunity of humans, and finally reaches the strengthening of the self guard and recovery systems in human body.

Acknowledgment

We are grateful to Professor C. H. Townes of the University of California at Berkley for his discussions and suggestions. We are also thankful to President E. Shoyama and Mr. H. Momoi of Hitachi Ltd. for their assistance on this University-Industry project research.

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