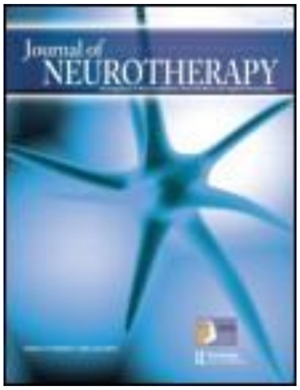

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Effects of Hemoencephalographic (HEG) Training at Three Prefrontal Locations Upon EEG Ratios at Cz

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Effects of Hemoencephalographic (HEG) Training at Three Prefrontal Locations Upon EEG Ratios at Cz

Robert Sherrill, Jr., PhD

SUMMARY. *Background.* Light in the wavelength region of 650 to 1000 nanometers is able to penetrate living human tissue, including bone. Medical research has exploited this optical window into the body to develop non-invasive monitoring of brain functioning. In 1994 Herschel Toomim discovered that he could both measure and teach persons to control the amount of oxygenated blood flowing in the prefrontal regions with such an optical device. He has labeled the biofeedback of brain blood flow hemoencephalography (HEG).

Methods. A fifteen-year-old male with a history of mild articulation problems and poor spelling was administered twenty sessions of combined HEG/EEG biofeedback, with a referential recording at Cz. Feedback in each session was conducted in three trials with the HEG optodes placed over the left eye, at midline, and over the right eye for ten minutes each. The order of placement was counterbalanced across trials. Changes in HEG levels within each trial were computed and plotted across sessions, as was the theta/beta ratio for each trial.

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Results. The subject clearly learned improved voluntary control over brain blood flow. The slope of increases of HEG within each trial improved across sessions at all three forehead locations. There were three indications from this case that HEG training to improve attention might be most efficacious at the midline location: (a) the theta/beta ratio at Cz decreased slightly over sessions only in response to HEG training at midline, (b) bursts of beta lasting ten seconds or more occurred more often, and (c) occasionally a marked increase in HEG within a trial was associated with a corresponding increase in power in beta. This occurred only with HEG at midline.

Conclusion. HEG biofeedback is a promising treatment modal-ity, especially for improving the functioning of executive control systems mediated by the prefrontal regions of the cerebral cortex.

KEYWORDS. Hemoencephalography, HEG, electroencephalography, EEG, rheoencephalography, REG, near-infrared spectroscopy, NIRS, blood flow biofeedback, biofeedback

INTRODUCTION

Hemoencephalography (HEG) is a recent addition to the technology of teaching self-regulation. It has potential for improving the functioning of the prefrontal lobes and thereby remediating executive skills such as sustained attention with far less interference by artifact than EEG biofeedback. HEG is possible because living human tissue, including bone, is translucent. Light shown onto the scalp can penetrate the skull and reach underlying brain tissue. Much of this light is scattered or absorbed, but a small proportion is reflected back through the skull to the surface (Toomim et al., 2000). Light in the wavelength region of 650 to 1000 nanometers (nm) is absorbed minimally by water or tissue and thus is reflected back especially well. Villringer and Chance (1997) reported that this wavelength region of red and infrared light "represents an "optical window" for the non-invasive assessment of brain tissue" (p. 438). Longer wavelengths in the infrared range, such as heat from blood, also radiate easily through the skull and other tissue.

Optical Techniques in Medicine

HEG is an outgrowth of medical research into optical technology for monitoring oxygen levels in the body. The best-known example is the pulse oximeter. It has been shown to agree very closely with measurements by standard blood gas machines over the range of 70 to 100% oxygen saturation (Williams, Mortimer, & McCollum, 1996). Because it is quick, non-invasive and accurate, pulse oximetry is now used routinely for continuous monitoring of oxygen levels in patients during surgery. Pulse oximetry uses time gating to measure only the pulse component of arteries (Owen-Reece, Smith, Elwell, & Goldstone, 1999). In contrast, HEG technology uses different wavelengths of light, which permits deeper penetration into the body. It provides a more global assessment of oxygenation in brain tissue, especially in the rich capillary beds of the cerebral cortex.

Optical technology in medicine is usually described as near-infrared spectroscopy (NIRS). Elwell, Springett, Hillman, and Delpy (1999) summarized the physical principles underlying NIRS and its usefulness in anesthesia and in adult and neonatal intensive care. Villringer and Chance (1997) remarked that NIRS might be especially helpful in situations where other neurodiagnostic technologies were impractical, such as persons ambulating, or children with attention disorders who could not lie quietly in brain imaging equipment. Hock et al. (1997) predicted a role for NIRS in psychiatry, especially for diagnosing or monitoring dementing disorders. Elwell et al. (1999) concluded that, “NIRS provides the opportunity for the continuous, noninvasive assessment of quantitative cerebral hemodynamics and oxygenation in the intact adult brain” (p. 63). An extensive bibliography of NIRS research is available at the website of the Biomedical Optics Research Group at University College, London, www.medphys.ucl.ac.uk/research/borg/pub_chro.html.

Benaron et al. (2000) reported that optical measurements showed high agreement in localization both with functional magnetic resonance imaging and with EEG signals. They concluded that, “. . . optical methods offer a single modality for exploring the spatio-temporal relationships between electrical and vascular responses in the brain in vivo . . .” (p. 469). A very close correspondence between localized changes in blood oxygenation and fluctuations in neural activity was also reported by Logothetis, Pauls, Augath, Trinath, and Oeltermann (2001). These findings make the monitoring of blood oxygenation an attractive “window into the brain” for learning neuronal self-regulation.

The Development of Brain Blood Flow Biofeedback

The earliest research into the biofeedback of brain blood flow measurements is reported to have begun in the Soviet Union in the 1960s. This was labeled rheoencephalography (REG). The variability in electrical impedance among various regions on the scalp produces a waveform from which arterial and venous components can be derived. Persons suffering from psychophysiologic disorders typically have relatively low arterial amplitude relative to their venous component.

A review of articles published on REG since 1990 in the electronic database of the National Library of Medicine (www.ncbi.nlm.nih.gov/entrez/query) showed most to have appeared in Russian-language sources. REG was employed in the diagnosis of circulatory disorders, cerebral injuries, hypertension, sequelae of radiation exposure, and the effects of acceleration and space flight. One study used changes in REG to measure the physiologic effects of meditation.

Changes in left prefrontal brain blood flow as a consequence of concentration were described by Villringer, Planck, Hock, Schleinkofer, and Dirnagl (1993) using NIRS technology. After a baseline of eyes-closed resting, subjects were instructed to perform mental calculations for one minute. Within a few seconds of this intentional cognitive stimulation levels of oxygenated hemoglobin and blood volume increased in 9 of 10 subjects.

Hershel Toomim became interested in blood flow technology while researching the physiologic effects of EEG biofeedback. A colleague sent him a reference on research by Britton Chance on cranial spectrophotometry. In 1994, while developing a device to record blood flow changes as a biofeedback outcome measure, Toomim discovered that he could change his own levels of oxygenated hemoglobin in the prefrontal region at will, and within a few minutes. He corresponded with Dr. Chance while developing his equipment for biofeedback, rather than for diagnostic measurement.

Toomim's device has been called "active HEG," since like other NIRS technology it shines light through the skull. It uses two different frequencies in alternating flashes: 660 nm, the bright red of oxygenated blood, and a reference stimulus at 850 nm, which is close to the dibestic wavelength that is independent of oxygenation. The proportion of 660 nm light reflected back varies far more than that of the reference frequency in response to how much red blood is in the capillaries in the underlying tissue. The HEG equipment calculates the ratio of these signals, which permits the HEG reading to be independent of the absolute values of the intensity or the path length of the reflected light. An estimate of the oxygenation of cerebral tissues can be made by Toomim's system, but not as accurately as a pulse oximeter. Consequently, HEG biofeedback emphasizes *changes* in oxygenated blood over time.

The light emitters and receivers are embedded in a neoprene headband, 3 cm apart. This spacing permits the light to penetrate about 1.5 cm into the underlying tissue, reaching the capillaries in the gray matter of the underlying cerebral cortex, before being reflected back in a banana-shaped path (Toomim et al., 2000). The headband is thick. It is held firmly against the forehead by an elastic strap. This prevents outside light from reaching the photo receiver on the headband. However, intense wrinkling of the forehead will permit outside light to leak in. This is the most important potential source of transient artifact in HEG recordings. Lesser degrees of muscle tension, or movements of the subject's eyes, do not affect HEG.

Other sources of potential error have been investigated, and found to be minimal. Only about 5 to 10% of HEG readings come from skin or skull tissue. This is because these body regions have little blood flow relative to brain tissue. Intense body movements will increase cranial blood pressure, but a clinician can observe this easily. Finally, calibration drift of the HEG instrument has been found to be less than 2% over six months (Toomim et al., 2000). Dr. Toomim markets his HEG device as the Thinking Cap™, through the Biocomp Research Institute. It is compatible with several biofeedback computer systems.

Jeffrey Carmen has developed a different approach to blood flow biofeedback with optical technology. This has been labeled "passive HEG," since it does not shine light into the body as Toomim's NIRS-based technology does. Instead, Carmen records HEG by means of a small camera strapped to the forehead, which measures infrared light emitted by the scalp and underling tissue in the range of 7 to 14 microns. These long wavelengths are well below the visible spectrum. Thus, Carmen's infrared equipment is completely insensitive to visible light. The camera has a field of view of a 32 mm diameter circle, about the size of a golf ball, focused upon the client's mid-forehead. Changes in blood flow in the brain cause localized changes in the temperature of the forehead, which the equipment can resolve down 0.01° Fahrenheit. It has a fast response time: temperature changes can be recorded and displayed in about 5 milliseconds. Eye movements and muscle tension have no effect upon the readings. The camera is recessed into a foam block, and so does not touch the scalp, which might distract the client. Dr. Carmen sells his HEG device through his office in Manlius, NY.

Carmen's practice is largely with migraine patients. He had used peripheral temperature training for years and had begun to experiment with infrared technology in treatment both to monitor migraine activity and to teach self-regulation. After becoming aware of Toomim's HEG system, Carmen began experimenting in early 1998 with recording infrared readings from the forehead rather than from the site of the migraine (Toomim & Carmen, 1999).

Initial Clinical Findings with HEG Biofeedback

Rheoencephalography (REG). Dr. Vlad Tokarev has posted a brief summary of REG at an English-language website (www.webideas.com/biofeedback/research/vtokarev.html). He describes one study in which REG biofeedback used to increase the participant's arterial/venous ratio was successful in decreasing emotional distress, hypertension, and production errors in factory workers.

Passive Hemoencephalography (HEG). Dr. Carmen has found that his migraine patients develop control over their symptoms far more quickly with HEG than with peripheral temperature training. He used both techniques together for a time, but has begun to rely more heavily on HEG. He suspects that HEG's clinical efficacy is a consequence of its enhancing the executive control systems of the prefrontal cortex rather than any direct impact upon malfunctioning vascular systems. Some of his patients have reported being able to abort the headache stage of migraine through their HEG training (Toomim & Carmen, 1999). In addition, about 50% of his clients who have depression coexisting with their migraines have reported spontaneous brightening of their mood. Finally, he has noticed that several persons with Attention-Deficit/Hyperactivity Disorder (ADHD) comorbid with migraine attained a normalization of attention during an HEG session, apparently due to suppression of frequencies below 12 Hz.

Active Hemoencephalography (HEG). Toomim et al. (2000) reported on a treatment group of 26 children and adults with various neurologic diagnoses. The majority (14) had been diagnosed with Attention Deficit/Hyperactivity Disorder. Each subject was seen for ten outpatient sessions. In each session he or she received HEG biofeedback with the path of the light centered over the left eye, the mid-forehead, and then over the right eye, in that order. The experimental participants showed a gain of almost one standard deviation on a demanding test of sustained visual attention (the TOVA™). A sham-treatment comparison group made insignificant improvements on the attention test.

Three of Toomim's participants from this study were administered Single Positron Emission Computerized Tomography (SPECT) scans prior to and following their HEG treatment. All three showed clear increases in cerebral blood flow after 10 sessions, both at the biofeedback sites and also at anatomically distant areas, such as the cingulate gyrus (see graphs in Toomim et al., 2000).

Frank Deits (2000) has reported differential effects of HEG training, depending upon the forehead location. Through extensive personal experience he found that training over the left eye enhances a state of mental readiness or focus and is useful when he is about to undertake a mental task such as computer programming. He has been able to interact with another person while training without decreasing his HEG readings. In contrast, training over the right eye produces more of a state of emotional readiness, which will be decreased if he interacts with another. He finds that training over the right eye quiets thinking and is useful before he goes to bed.

Case Study. In response to the report by Deits (2000) of differential effects from training at the left and right forehead sites, the author decided to vary them systematically for this case study. Because change in readings over time appears to be more important in HEG biofeedback than absolute levels, the experimenter decided to assess voluntary control in terms of increased ability to change HEG readings within sessions. That is, would the subject show improvement *across* sessions in his capacity to voluntarily influence HEG readings *within* each session? In other words, would voluntary control improve with practice?

METHODS

The participant was a fifteen-year-old, right-handed male with a history of moderate delay in the development of speech, and continuing mild articulation problems and poor spelling. He had attended a special preschool for his articulation delays. His academic progress in public school had been adequate with the exceptions of his spelling and his capacity for expository writing. A quantitative electroencephalogram (QEEG) at age ten had been interpreted as showing mild left frontal abnormalities in both long and short connections. His most deviant scores had been in phase in the alpha band (F1T5 = −1.98; F701 = −2.12; F301 = −1.99) and in left hemisphere amplitude asymmetry in the delta band (F1F3 = 2.64; F1P3 = 2.04). He did not have any history of attention problems and all his scores on the Integrated Visual and Auditory Continuous Performance Test had been well within normal limits.

He had become acquainted with optical technology as part of a school science fair project. He volunteered to test HEG biofeedback as a personal experiment, even though he was not a formal client, to see if this would improve his expressive-verbal skills. He completed 20 sessions of combined HEG/EEG biofeedback over a period of 13 weeks. Toomim's Thinking Cap™ device was modified for use with the Focused Technology ™ biofeedback system. The primary emphasis was increasing the subject's HEG, although levels of 4-8 Hz (theta) and 15-18 Hz (beta) from Cz referenced to linked ears were also displayed. EEG was recorded to see if HEG biofeedback would have any impact upon generalized attention, and if this would vary with HEG training at different forehead locations. Feedback in each session was conducted in three trials, with the HEG optodes centered over the left eye, mid-forehead, and right eye for 10 minutes each. The order of placement was counterbalanced across trials (see Table 1). Informal verbal encourage-

TABLE 1. Order of Optode Placement Access Trials

OPTODE PLACEMENT (10 minutes apiece)			TRIALS			
L	M	R	1	7	13	19
M	R	L	2	8	14	20
R	M	L	3	9	15	
L	R	M	4	10	16	
M	L	R	5	11	17	
R	L	M	6	12	18	

Note:
L: designates left eye
R: designates right eye
M: designates mid-forehead

ment was given during trials for increasing HEG. Changes in HEG levels within each trial were estimated by computing the ratio of the mean HEG for the entire 10 minutes, divided by the mean HEG for the first six seconds of recording. (This metric has been recommended by Toomim as the most stable measure of HEG changes.) The subject's measure of voluntary control was plotted across sessions, as was the ratio of theta/beta for each trial.

RESULTS

Voluntary control of HEG within a trial increased steadily across sessions at all three forehead locations. Figure 1 shows the results for all sixty trials. The figures for each location showed an almost identical slope and variability. Figure 2 shows a stepwise regression which revealed session to be the only significant variable (T = 4.73, P < 0.001).

The theta/beta ratio showed essentially no change over the course of training (Figure 3). In the first session it averaged 2.32 for all three trials and in session 20 it averaged 2.55. Thus, the subject was able to increase his control over HEG without a frequently used EEG marker being sensitive to this.

FIGURE 1. HEG All Trials

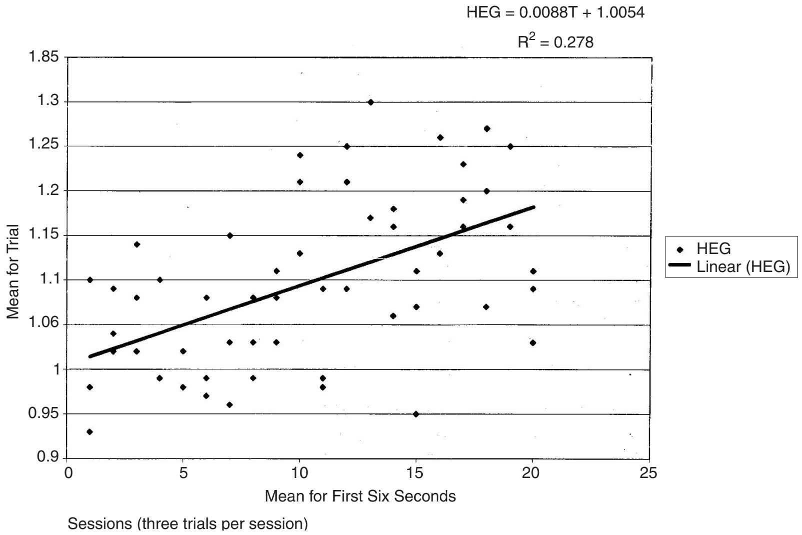


FIGURE 2. Main Effects Plot–Data Means for HEG

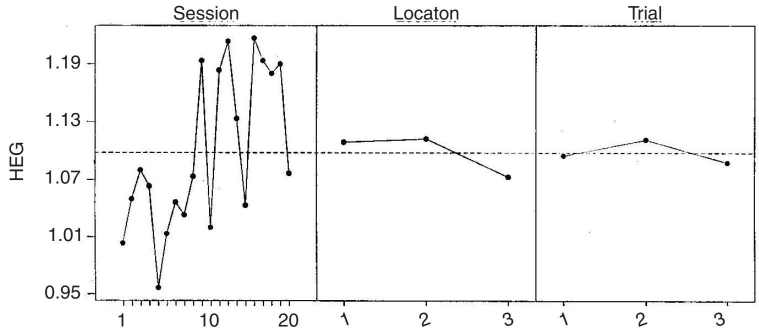
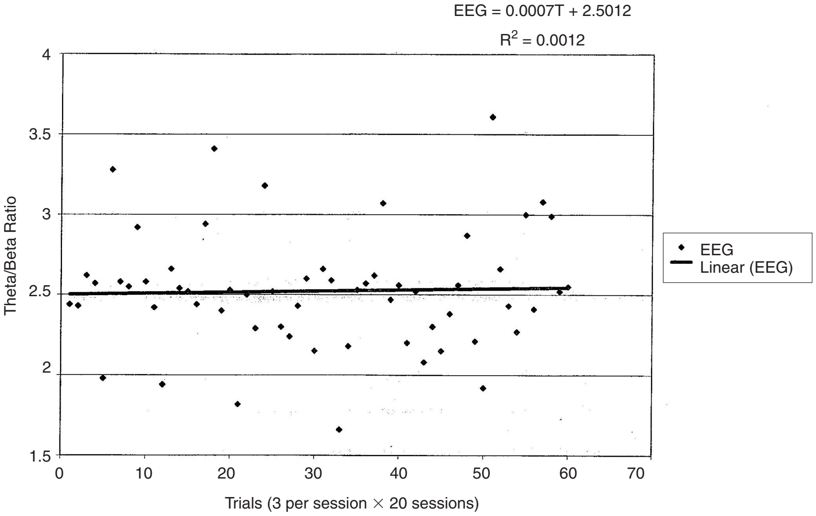


FIGURE 3. EEG All Trials



The subject did not identify any clear improvement in his spelling or writing by the end of his training. However, a QEEG recorded three months later indicated some resolution of his electrophysiologic dysfunction. Phase deviance in the alpha band decreased as follows: F1T5 from −1.98 to −1.62; F7O1 from −2.12 to −1.3; and F3O1 from

−1.99 to −1.02. Left hemisphere amplitude asymmetry in delta decreased at F1F3 from 2.64 to −0.58, and at F1P3 from 2.04 to −0.12.

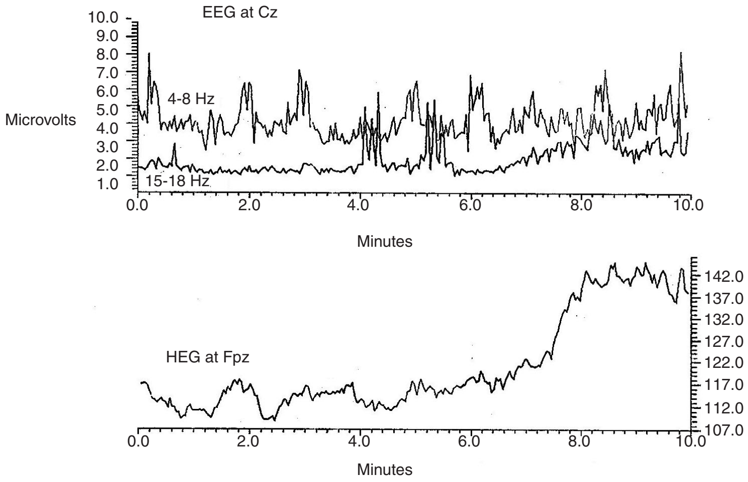
There were three indications from this case that HEG training to improve attention might be most efficacious at the mid-forehead location:

1. The theta/beta ratio decreased slightly (although insignificantly) over sessions only in response to HEG training at mid-forehead. When the HEG optodes were in the right-forehead and left-forehead locations, the theta/beta ratio actually worsened slightly over sessions. (Dramatic improvement in theta/beta ratios had not been expected, since the subject did not suffer from a primary attention disorder.)
2. From the printed graph of each trial, the experimenter performed a manual count of instances in which bursts of beta lasted 10 seconds or more, and exceeded the voltage levels of theta activity even briefly. As Table 2 shows, during the first 10 sessions these bursts occurred with roughly equal frequency when the HEG optodes were at each of the three forehead locations. However, during the last 10 treatment sessions, bursts of beta decreased markedly when HEG biofeedback was being conducted at the lateral locations, and occurred more often only when HEG was at mid-forehead. This may represent a spontaneous physiologic operant shaping of the tissue activated by biofeedback information. That is, in response to sustained feedback at any location, only that tissue directly relevant to the feedback information continues to be influenced by it, and thus the total tissue volume responding to the biofeedback information decreases over time.
3. There were a few instances during training where a marked increase in HEG within a trial was associated with a corresponding clear increase in power in beta. Figure 4 displays the most dramatic example, beginning at about minute six. These instances occurred only when HEG training was being conducted at mid-forehead.

TABLE 2. Changes in Bursts of 15-18 Hz Across Training

	BURSTS OF 15-18 Hz Lasting 10+ seconds, and exceeding 4-8 Hz even briefly		
	LEFT	MIDDLE	RIGHT
SESSIONS 1-10	38	22	26
SESSIONS 11-20	19	25	6

FIGURE 4. Increase in 15-18 Hz EEG Corresponding to Increase in Mid-Forehead HEG



As HEG begins to rise markedly at about minute 6, the power in the EEG range of the 15-18 Hz also begins to increase.

DISCUSSION

These findings have all of the limitations of any single-case study. Although the experimenter believed that the most changes in voluntary control might occur in the left-forehead location, in view of the participant's history and QEEG findings, improvements occurred equally at all three forehead locations. The theta/beta ratios decreased slightly at Cz only in response to the mid-forehead HEG biofeedback. Of course these findings will need to be replicated with subjects experiencing a variety of brain disorders.

Clinical experience with both active and passive HEG biofeedback, although limited thus far, suggests blood flow training to be promising. The equipment is relatively inexpensive. Client setup is quick and simple. Instrument response times are fast.

Artifact-inducing client behavior, such as frowning, is easily observed. Paraprofessionals could be trained to conduct treatment sessions under supervision, which would reduce costs in settings where several clients were training simultaneously, such as an after-school program. These advantages give HEG training the potential for being for biofeedback treatment what the Model T or Volkswagen were for automobile transportation: sturdy, effective for many needs, and sufficiently inexpensive to promote widespread use.

Client learning appears to occur quickly. This, and the intuitive feel of the biofeedback, is motivating for the client. Ease of access to the prefrontal areas makes HEG biofeedback an attractive option for treating a variety of disorders by strengthening executive control systems. These include not only bipolar disorder and migraine headaches, as already reported, but also Attention-Deficit/Hyperactivity Disorder and traumatic brain injury. Since the frontal lobes are crucial for the qualities such as self-reflection and empathy which make us most human, HEG biofeedback may be a means of promoting humaneness beyond the treatment of obvious clinical dysfunction.

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