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New Developments

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In the near future, several lines of development that are now in the research domain will likely produce techniques and technologies that are clinically relevant. Although currently in various stages of refinement, these are mentioned because they may provide a more immediate usefulness for the laboratory wishing to push beyond routine digital electroencephalography (DEEG). For completeness, this report will include new technologies that are just entering into the marketplace and are therefore not strictly speaking groundbreaking.

ELECTRODE SYSTEM

In the quest for more accurate localization with a noninvasive recording technique, the logical approach is to increase the spatial sampling density by using a greater number of scalp electrodes to cover the same scalp area. As complex head and brain models are developed and achieve more realistic results, they will require these high recording densities. Although 20 years ago 16-channel electroencephalographs were rare and desirable (whereas 8-channel was the norm), today no serious laboratory uses anything less than the full set of International 10-20 System positions.

Various systems for the application of more than 32 scalp electrodes have been described. Specifically the methods used by Fender (1987), Itil and Itil (1986), and Musha and Homma (1990) are worth mentioning within an historical perspective. The most popular in one form or another is an elastic mesh-type cap with embedded electrodes that can provide up to 130 electrodes for clinical or research use and still achieve a reasonable compromise between setup time and quality of the electrode interface (i.e., impedance, stability, or comfort). With practice it is possible to apply a 100-electrode cap with good results in less than 2 hours.

Typically elastic straps around the chin or across the upper chest tie down the device (whether cap, grid, or elastic mesh). Despite this they tend to shift around the head, as they cannot be strapped down too tightly and still maintain comfort. The main problem with using an elastic cap device is therefore shifting of the cap position, with the secondary problem of electrode paste smearing due to such movements. Additionally, unless the cap is custom-made for a given head, it seldom fits the standard International 10-20 System positions. This makes it quite impossible to compare or localize EEG findings across different patients. One solution is to combine the patient's magnetic resonance imaging (MRI) scan (see below) in order to project each electrode onto the scalp and cortical surfaces. This procedure is rather complicated and is not suited for routine clinical recordings.

Although there is general agreement that more than 20 scalp electrodes will result in improved localization of intracranial sources, there is a point of diminishing return. Nunez (1981) provided some theoretical background that serves as a guide, although his computations may not be applicable to clinical situations. Yvert et al. (1997) suggested that going from 19 to 32 channels improved localization by 2.7 mm, and going from 32 to 63 improved it by <1 mm. These estimates were based on a spherical and not realistic head model and therefore may not be applicable under all circumstances. The optimal number of electrodes depends on the application: at one extreme brainstem-evoked potentials use only three positions, due to the nature and requirement of the analysis. For cortical somatosensory evoked potentials from simultaneous bilateral stimulation, continual im-

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provement of scalp localization of the individual right and left hemispheric response can be seen right up to 128 electrodes (Gevins et al., 1991).

There are devices in use that measure electrode positions accurately. The original system, of course, is the use of the tape measure or calipers. Recently, three-dimensional positioning devices have been used and prove to be versatile and easy to use. A map of the exact electrode positions can be produced quickly and displayed onto a head model, for example, based on the patient's MRI head scan. This and similar kinds of measuring devices will facilitate the application of large numbers of electrodes and yet keep track of where they are in relation to known fiduciary skull markers (e.g., preauricular points, nasion, and inion). The addition of anatomic information (MRI) allows each electrode's position to be known in relation to cortical surface landmarks, thus providing a higher level of anatomic localization.

AMPLIFIER IMPROVEMENTS

Advances in solid-state integrated circuit design and fabrication have produced single-chip, low-power multichannel amplifiers and high-precision, 16-bit analog to digital converters. This combination allows a simple EEG front-end design: the amplifier need only be of low noise and fixed gain, followed by a software-controlled filter, then the 16-bit analog to digital converter. All of these components can be housed in a small head box, with the digital output being optically coupled to the computer in order to achieve electrical isolation. This coupling may be either by a physical cable or by infrared wireless transmission.

The advantage of having 16 bits of precision yields a very high dynamic range so as to be able to record from a noise level of 1 μV, to a maximum range of ±32 mV, even if no amplification was used (i.e., gain = ×1). Such simplicity translates into an inexpensive front-end design even for 128 channels.

DISPLAY

Computer video display devices now routinely achieve resolutions of 1,600 × 1,200 (number of horizontal and vertical dots or pixels, respectively). There are solid-state flat display panels which can yield such a high resolution in color. The trend is toward larger screen dimensions, smaller pixel size (pitch), brighter light output, and lower power consumption (for cooler operating temperature and portability).

COMPUTER HARDWARE

Nowhere else is there a more frantic pace of progress. Intel Corporation's Pentium II® central processing unit chip at 400 MHz clock rate is the rage at the time of this writing. However, manufacturers are outdoing each other with announcements of higher clock speed, greater cache memory, more functionality, smaller size, or lower power consumption. It is likely that by the time this issue is published, the latest chip may well be another generation ahead. The net benefit of more powerful CPUs is a much more interactive and responsive DEEG unit, even if loaded with more complex analytical and display algorithms.

The same trend is present with regard to computer memory (both random access memory or RAM and storage device memory such as that kept on a hard disk). This will allow larger and more complex software programs to be built and provide support for the new central processing unit chips that require prodigious amounts of RAM to operate; 64 MB of RAM will be seen as minimal.

Simultaneously, there is also a trend toward a smaller physical size and lower power requirement for the manufacturing of portable laptop computers. Several vendors have already successfully used commercial laptop devices to house their DEEG design. New interface devices such as the wireless keypad or mouse and wireless data transfer will provide a small but useful ergonomic improvement. It is not too wild to suggest that with wristwatch-sized computers there may be novel applications for "ambulatory" EEG.

The other major barrier to a proliferation of EEG systems in everyday applications is price. If small and inexpensive DEEG units became available it is likely that new applications would be devised. One important and probable application is the monitoring for fatigue under mission-critical conditions: e.g., long-distance truck driving, piloting aircraft, or performance of delicate repetitive operations. By the time this article appears in print, the price of an entry-level DEEG system may well drop below $10,000. It is not difficult to envisage the hardware cost for reader stations to be under $1,000 before long. This downward trend in the cost of hardware does not necessarily hold for software, though.

COMPUTER SOFTWARE

With more powerful CPUs and massive amounts of memory all running at lightening speed, the stage is set for the next generation of DEEG software. The mundane chores of acquiring EEG signals, managing montages and amplifier settings, and storing to disk can all be done with the central processing unit merely at idle. Some additional functions that can be added in real-time include seizure monitoring, spike detection, artifact recognition/correction, and pattern recognition of specific background activity patterns (e.g., sleep staging).

Specific analysis designed for the neurointensive care environment can also be integrated in the routine DEEG unit, making it a truly multipurpose device suitable for all aspects of clinical neurophysiology.

In yet another aspect, report-generating functions can include custom-designed reporting software, as well as voice-input/text output software (voice recognition). The latter can even be used for direct voice annotation (if desired) during data collection, rather than using the keyboard.

NETWORK–CONNECTIVITY

Most new computers now have integral chips in the motherboard for a variety of control functions: hard and floppy disk, video display, and modem and network interface. It is a simple matter to include remote control capability into the software. Then EEGs can be recorded in the intensive care unit or the operating room while the tracing is displayed simultaneously on the screen at the patient's bedside, as well as over the hospital's local area network (LAN) cable to the desktop computer of the physician in the EEG Department. A similar scenario can be achieved over the telephone wire to another remote location, perhaps in the next city. It would be straightforward to include remote control of the recording process, in addition to passive review of the real-time EEG data. Such degrees of connectivity (both local and wide area networks) are a direct benefit of the tremendous spin-off advances from consumer Internet popularity.

DIGITAL VIDEO

Some laboratories have instituted video recording during routine outpatient EEGs. The advantage is that any episode (of clinical or electrographic interest) can be captured and corroborated with the EEG. This requires a careful attention to synchronization of the video signal with EEG. However, as a result this generates a huge amount of data: until recently, the only practical storage medium is the videocassette recorder.

Despite its popularity, the videocassette as a storage medium is not particularly desirable for this kind of monitoring, particularly because constant back-and-forth searching is often required. Its disadvantages include being inconvenient (serial access rather than random access storage) and bulky (prone to minor video signal quality problems, particularly with thinner tapes and prolonged use). However, the advantages include being inexpensive, relatively compact, and widely compatible (i.e., universal standards exist).

With improvements in memory and new methods of video compression, such issues of storage requirement become much easier to handle satisfactorily and affordably. Current compression standards of Joint Photographic Experts Group and Moving Pictures Experts Group are recognized, and newer encoding algorithms are being tested for yet greater efficiency. On the storage medium side, small inexpensive hard disk drives are now 10 gigabytes (GB) in capacity. There are manufacturers currently testing devices which can hold >24 h of video as an alternative to the videocassette recorder. With the digital versatile disk (DVD) becoming a standard, storage costs will take another fall, because each DVD can hold 4.7 GB of data on each side of a single platter the size of a CD.

CORTICAL SIGNAL ESTIMATION

One of the goals of EEG interpretation is to accurately identify and localize the electrical generator of any interesting waveform. Whereas traditional paper EEG has succeeded with the pattern recognition of waveform morphology without the need for new technology, intracranial localization still presents a hurdle.

The first attempt to infer intracranial generators (or sources) made use of the mathematical function called the Laplacian, which represents a measure of the current flow into and out of the skull (current source density). Numerical implementation was successfully completed by Hjorth (1975), using a very simple and elegant algorithm. Perrin et al. (1987) improved on this by using a more refined mathematical model of the EEG across the scalp, thereby increasing the accuracy of current source density measures. Various investigators have used the dipole localization method based on a spherical head model. Ebersole (1991) and Ebersole and Wade (1991) studied temporal lobe sources in complex partial epilepsy and demonstrated that the orientation of interictal spikes (using dipole localization method) can predict outcome after temporal lobectomy. The topography of interictal rolandic spikes was found to be associated with the number of seizures, leading to the hypothesis that generator site (fissural or gyral) influences the epileptogenicity of a seizure focus (Wong, 1998).

Doyle and Gevins (1986) and Sidman et al. (1978) used similar spherical dipole-sheet models to compute wider areas of cortical source activity. Scherg and von

Cramon (1985) described different methods of computing intracranial sources from the scalp EEG.

However, all these methods did not account for skull thickness variations (e.g., thinner at the temporal and thicker at the parietal areas), which can cause large variations of signal attenuation. In effect, they assume a uniform skull, usually of spherical shape, and thus incapable of being customized for a particular human head. Waberski et al. (1998) described a method of utilizing the exact skull shape, showing that it improves the localization of dipole localization method results, especially within the temporal region of the brain with particularly convoluted anatomy.

Gevins et al. (1991) described a method called "deblurring" which in essence removed the blurring effect of the skull, using individual anatomic information based on each individual's MRI head scan. Thus, the exact skull shape and thickness at every point are accurately measured and used in the head model. The result is the first realistic estimation of electrocorticography obtained without the need of surgery (craniectomy).

The same technology has been applied to the measure of higher cortical functions such as working memory (Gevins et al., 1996). While this is not the traditional concern of the clinical neurophysiologist, in some aspects such information ties in very well with traditional EEG goals, namely the understanding of normal and abnormal brain functions. In the particular area of epilepsy surgery, it is indeed critical to identify and localize areas of pathology as well as critical and eloquent areas (e.g., speech and motor functions).

NEW HORIZONS

Given the rapid pace of technological advances in hardware and software engineering, the limits to growth in clinical neurophysiology may well lie in the successful transformation of research techniques to the clinical arena. It is a fact that ideas previously thought impossible due to technical limitations are being implemented routinely (e.g., the 128-channel DEEG machine). It is not possible to predict which of the wild and wonderful research ideas being discussed today will be relevant tomorrow.

Such a state of affairs is exciting but also fraught with potential pitfalls. It provides a great opportunity for EEG practitioners to meet the challenge and evolve, thus pushing the limits of neurophysiology into new territory. Who can predict when noninvasive 'virtual reality' electrocorticography can be performed for the localization of a tumor or seizure generator?

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