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SPECTRAL ANALYSIS OF THE EEG IN MEDITATION[1]

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Several investigators have reported changes in the EEG of normal adults induced by yoga meditation: Das and Gastaut (1957) recorded fast frequencies during deep states of meditation. Anand *et al.* (1961) pointed out the prominence of alpha activity associated with the absence of reaction to external stimuli. More recently Wallace (1970) remarked the appearance of theta waves in the frontal area during the practice of Transcendental Meditation (TM). The purpose of this study was to seek further evidence of EEG alterations to determine whether meditative states can be distinguished from other states of consciousness. To test this hypothesis we compared twelve subjects practising TM, as taught by Maharishi Mahesh Yogi (1966), with adequate controls. Methods of classical electroencephalography were combined with computerized spectral analysis and correlated with subjective data. The present work has been the subject of a preliminary presentation (Banquet 1972).

METHODS

Subjects

The study was carried out on twelve experimental subjects (9 males, 3 females) and a group of twelve matched controls who were about to learn TM. Three of the controls (2 males and 1 female) were also experimental subjects and were tested before and after starting meditation. All subjects volunteered and were obtained through the Students International Meditation Society, Cambridge Center. The method, described as a mental repetition of a special sound or Mantra, was imparted individually to meditators. All of them had practised TM daily during two 30 min sessions over a period ranging from 9 months to 5 years with an average of 24 months. The group was composed of one undergraduate, six teachers of TM, three office workers and two college faculty members. The mean age was 30 with a range between 23 and 52. The control group consisted of two college faculty members, one undergraduate, one Ph. D., and eight office workers (mean age 29 years 9 months, range 18–58).

Procedure

The experiment was conducted in a soundproof room, dimly lit for observation purposes. Subjects were seated comfortably. Records, with linked ears for reference electrode, were taken from electrodes F3,4 C3,4 P3,4 O1,2 of the 10–20 system. The time constant was 300 msec, the high pass limitation 60 c/sec, the EEG machine a Grass Model 78 polygraph. The EEG was recorded on paper and stored on tape (Ampex, 7-channels).

In 6 experimental subjects the EMG was recorded from a surface electrode applied below the chin with linked ears as reference electrode. The respiratory rate and amplitude were studied with a Grass TCT-IR thermocouple transducer fixed to the right nostril and linked to a polygraph DC driver amplifier.

A push-button with a code of 5 signals permitted the subjects to indicate the psychological events occurring during meditation or relaxation: body sensation, involuntary movement, visual imagery, deep meditation and

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transcendence (deepest point of meditation). A phone dial at the disposal of the operator signalled the EEG segments of special interest on paper and tape.

The planning of the experiment was explained to the subjects as follows: (a) Rest 5 min with eyes open and 5 min with eyes closed. (b) Meditate for their usual time of meditation (about 30 min) or, for the controls, relax for 30 min with eyes closed. (c) Come progressively out of meditation or relaxation (3 min). (d) Concentrate on a thought or image with eyes closed for 5 min. (e) Open the eyes.

Once the experiment was over, an interviewer investigated the quality and the events of meditation and relaxation. The number of sessions ranged from 1 to 10.

Data analysis

The entire sequence of record from O1 (with 6 meditators and 6 controls, also from C3 and F3) was filtered by a band-pass filter (0–60 c/sec) and digitized at a rate of 200 points/sec (or 100/sec for the specific study of low frequencies). These data were stored on Dectapes of a PDP 7 general purpose computer.

The spectral analysis was performed by Fast Fourier Transform, in the band 0–50 c/sec. A program used the Fourier Transform to produce a succession of EEG spectra in time (Gabor 1946). Each line of the plot made by a Calcomp plotter represented the Fourier analysis of 128 data points, *i.e.* 1.28 or 0.64 sec for the sampling rates of respectively 100 and 200/sec. The separation of these curves along the time axis covering the entire duration of the experiment was either 0.5 or 1 sec. On the X axis are the different frequency bands, with a resolution of 1 c/sec (Fig. 1,5). The Y axis represents the relative voltages of the different frequencies. A second program computed the integration over the 4 frequency bands: delta 0–3, theta 4–7, alpha 8–14, beta and fast frequencies 15–50 c/sec.

RESULTS

The results are derived from the comparative interpretation of the conventional EEG and frequency spectrum arrays, for both control and experimental subjects.

Control group

These subjects can be divided in two subgroups: alpha minus and alpha plus groups.

Alpha minus group

Four subjects showed beta dominant mixed frequencies throughout, with muscle activity

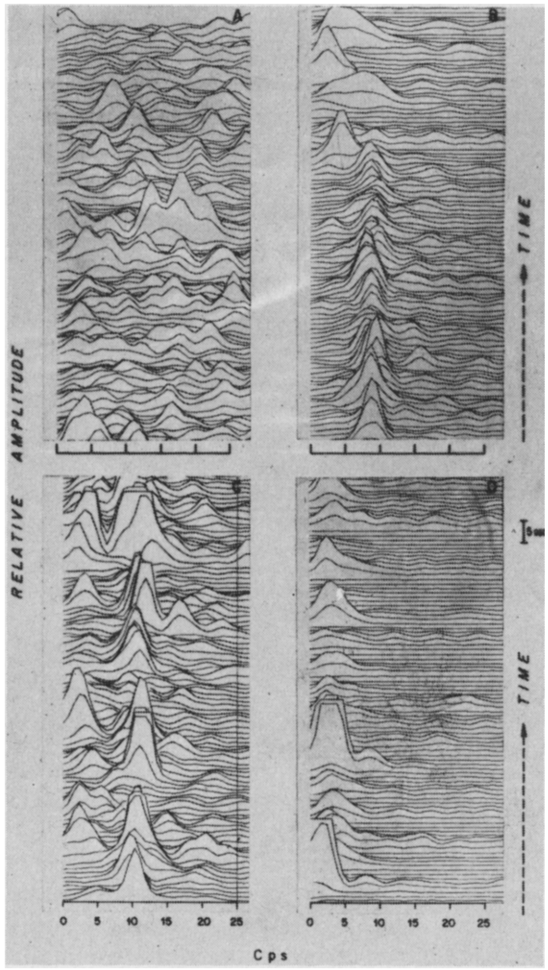

Fig. 1. Portions of spectral analysis plots from electrode O1 in four control subjects, during relaxation with eyes closed. *A*: Alpha-minus subject with beta dominant mixed frequencies and muscle artifacts. *B*: Alpha-plus subject with alpha rhythm at 9 c/sec shifting to theta and delta activity of drowsiness at the end of the period. *C*: Subject during drowsiness with mixed frequencies; short alternations of 10 c/sec alpha rhythm and delta frequencies at 2–3 c/sec. Notice the small amount of theta activity. *D*: Higher voltage delta activity and disappearance of alpha frequency. As a feature of the plotting program, the peaks were cut off when the amplitude reached a predetermined level.

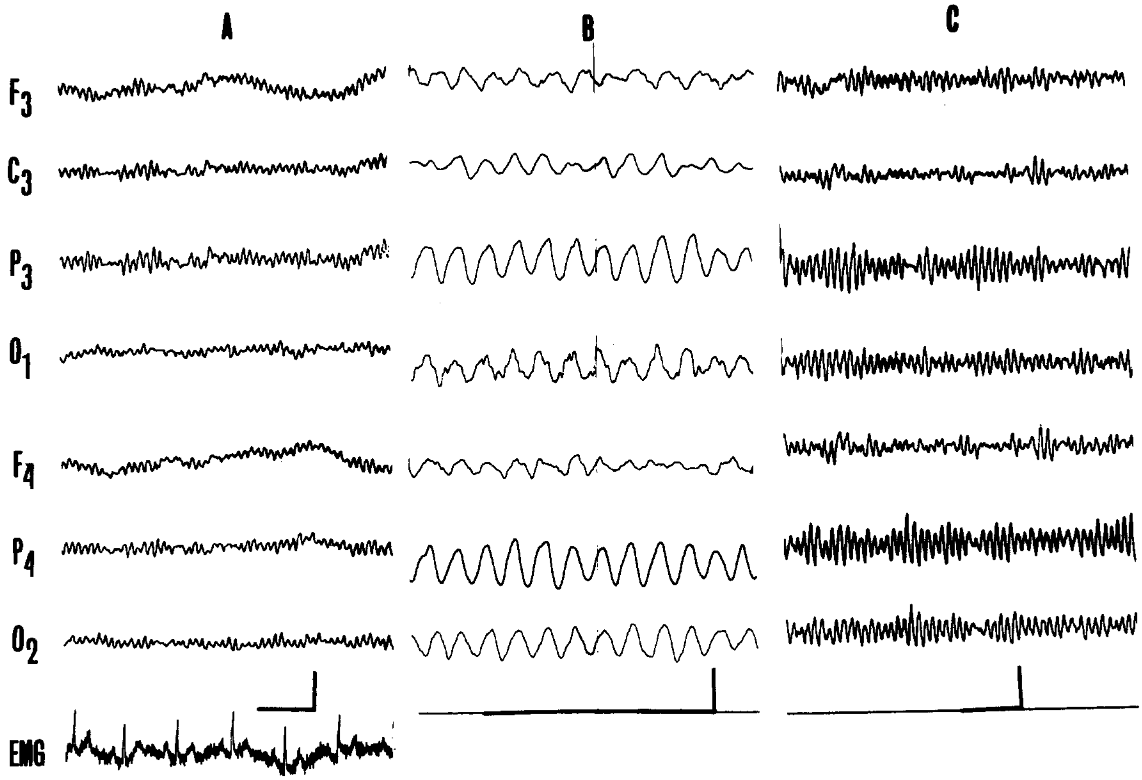

Fig. 2. Alpha frequencies at the beginning and the end of meditation in three subjects. In this and the following figure, vertical calibration = 50 μV, horizontal = 1 sec. *A* : First stage of meditation 10 min after the beginning. All the channels display a similar alpha rhythm at 9 c/sec, 30 μV. The EMG still presents some muscle activity. *B*: The recording speed at 60 mm/sec shows a slow alpha frequency at 8 c/sec, 30–60 μV, homogeneous in all channels at the end of stage 1. *C*: End of meditation. High voltage alpha waves at 9 c/sec, 60 μV maximum amplitude. In P and O channels the spindles are continuous and merging into one another.

superimposed on the spectrum. They did not develop a stable alpha rhythm during relaxation with eyes closed (Fig. 1,*A*).

Alpha plus group

Eight subjects developed an alpha rhythm at a constant frequency (Fig. 1,*B*).

(1) Four subjects of this group alternated posterior alpha waves with the previous pattern of beta dominant mixed frequencies. Muscle artifacts decreased or disappeared during the alpha periods. We could term this state a successful relaxation.

(2) The four remaining subjects associated alpha activity with slow theta and low voltage delta frequencies (Fig. 1,*B*, *C*) The paper record showed a relatively low voltage mixed frequency during this time, and drowsiness was reported. Two of the subjects presented periods of high voltage delta waves of sleep, with disappearance of alpha activity (Fig. 1,*D*).

Meditators

Meditation was associated with changes in the different parameters characterizing the brain waves.

Amplitude and frequency changes

The general tendency was for an early shift from the basic alpha rhythm to slower frequencies and, in four subjects, the emergence of a stable rhythmic beta activity at 20 c/sec.

(1) Alpha activity around 10 c/sec and 50 μV was present in the resting record of all the meditators. This frequency became predominant at the beginning of meditation (Fig. 2,*A*). Its amplitude increased up to 70 μV; in 10 subjects, the frequency slowed down by 1 or 2 c/sec, first in

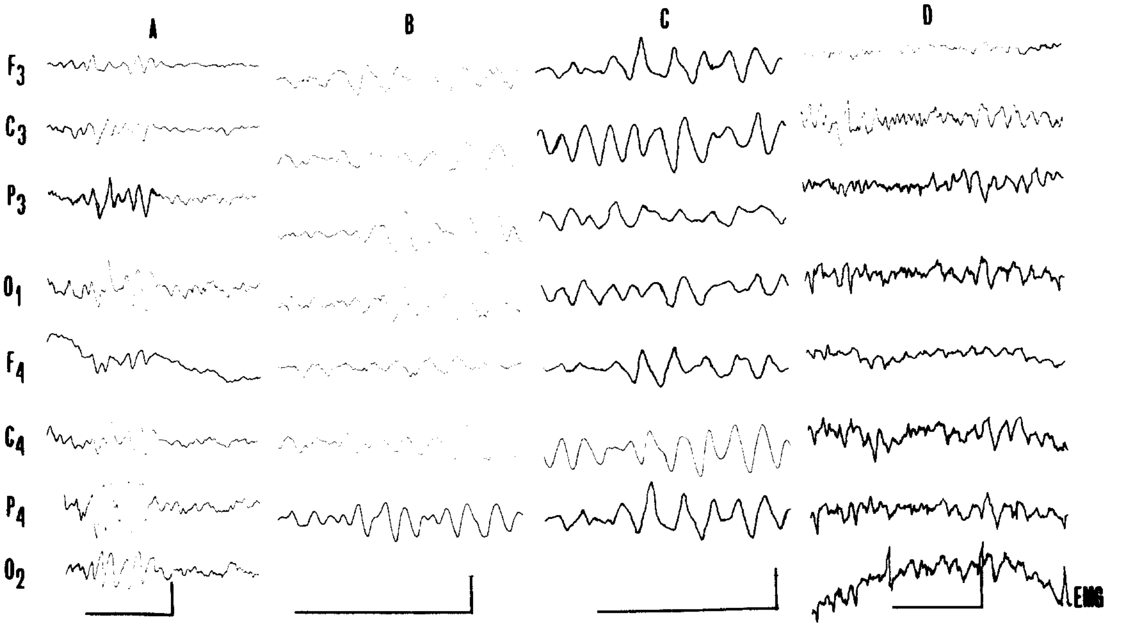

Fig. 3. Second stage of meditation. *A*: Theta burst at 7 c/sec and 80 μV recorded at 30 mm/sec. *B*: Transition phase from alpha to theta frequency. The recording speed of 60 mm/sec shows the theta waves at 6 c/sec appearing first in the frontal channels. *C*: Beginning of a theta train with simultaneous shift from alpha to theta frequency. *D*: Predominant theta frequency at 6 c/sec recorded at 30 mm/sec.

the frontal channels (Fig. 2,*B*). The pattern of this first stage of meditation was repeated at the end of TM with an even greater abundance of alpha waves, the spindles becoming continuous or merging into one another (Fig. 2,*C*).

(2) After the first stage there was a typical shift from dominant alpha to slower activity. If alpha waves appeared in this second phase they took the form of short bursts of a few seconds. A dominant theta pattern (unlike that of drowsiness) was observed in the second stage of meditation. Within 5–20 min after the beginning of meditation short bursts of high voltage (up to 100 μV) theta frequency at 5–7 c/sec occurred during 1 or 2 sec, simultaneous in all channels (Fig. 3*A*) or first in the frontal region (Fig. 3,*B*). Longer rhythmic theta trains (10 sec to several minutes) at 60–80 μV usually followed (Fig. 3*C*,*D* and 5,*C*). No further evolution in the meditation state happened in most subjects.

(3) In four of the meditators a third stage occurred, signalled with the push-button as being deep meditation or even transcendence. It was characterized by a pattern of generalized fast frequencies with a dominant beta rhythm around 20 c/sec. Das and Gastaut found similar fast frequencies during Krya Yoga Meditation. On the ink-written record this fast activity appeared as beta periods at 20 and 40 c/sec. Intermittent spindle-like bursts alternated first with alpha or theta rhythms (Fig. 4,*A*,*B*,*C*). They showed a tendency to become continuous on a persistent background of slower activity (Fig. 4*E*). This amplitude-modulated activity reached a surprisingly high voltage (30–60 μV). It predominated in the anterior channels but was present and sometimes simultaneous in all of them (Fig. 4*B*,*C*).

In the spectral arrays, the beta peaks lay nearly on a straight line, *i.e.* at an almost constant frequency (Fig. 5,*D*), with a high voltage beta peak at 20 c/sec and small amplitude fast frequencies around 40 c/sec.

(4) These 3 phases of meditation were not individualized clearly. The change from one dominant frequency to another was progressive. Two major frequencies could appear simultaneously in the different transition periods: alpha and theta or slow and fast frequencies (Fig. 5,*B*,*D*). If meditation lasted longer than the average

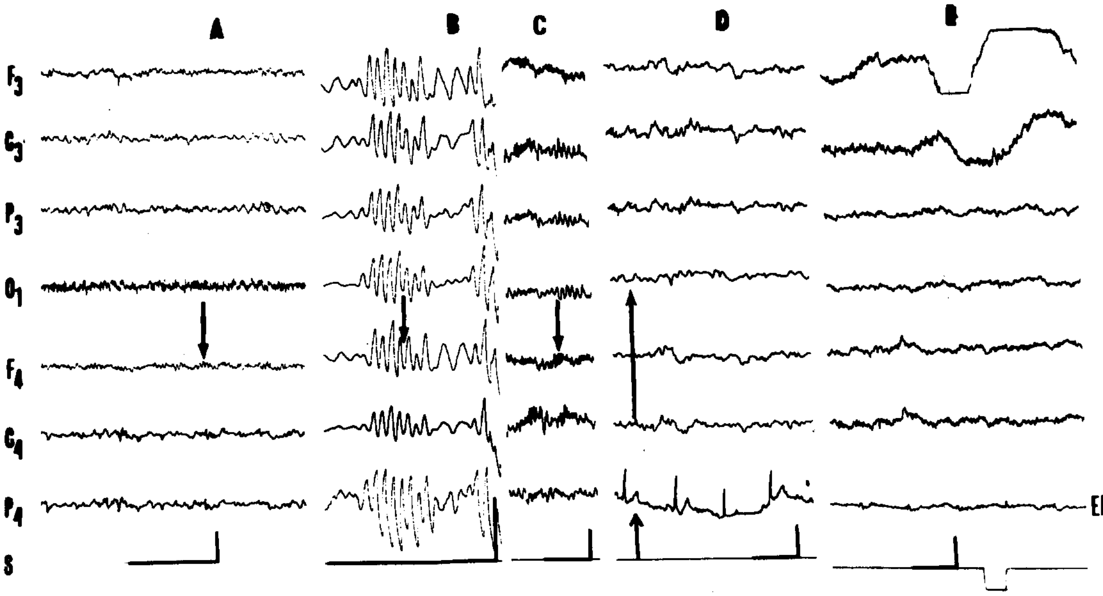

Fig. 4. Beta frequencies during meditation. *A, B, C*: The 3 arrows show the same pattern of spindle-like amplitude modulation recorded at 30, 60, 15 mm/sec. Notice in *B* and *C* the simultaneous occurrence of the spindles in the different channels. The frequency is around 20 c/sec. *D*: Disorganized pattern with beta rhythm at 20 c/sec on a background of mixed frequencies. Notice the absence of muscle activity in the EMG and compare with the EMG of Fig. 2,*A* from the same subject in stage 1 meditation. The ongoing pattern is not altered by the click stimulation indicated by the arrows. *E*: Fast frequency on a background of slower activity of small amplitude and absence of activity in the EMG. The subject indicates by the signal the deepest phase of meditation called transcendence. *A, C, E* come from the same subject.

30 min several cycles took place. The end of meditation was characterized by the return of alpha trains (Fig. 2,*C*). In advanced subjects alpha, and more rarely theta, waves persisted in the post-meditation period with eyes open. The concentration exercise after meditation produced alpha activity and brief periods of dominant beta frequencies (Fig. 6).

The changes observed during the different stages of meditation somewhat reduced the differences between the EEG channels, bringing about similar brain wave patterns in all of them.

Topographical changes in the EEG rhythms during meditation

Two kinds of topographical change could be observed: on the one hand, there was a constant tendency to synchronisation of the anterior and posterior derivations. Alpha rhythms spread from the occipito-parietal to the anterior channels, resulting in a possible gradient shift (Fig. 7,*A, B*). Theta and beta frequencies, which usually appeared first in the frontal channels, diffused posteriorly. On the other hand, a transient asymmetry between right and left hemispheres could occur in the shifting phase from slow to fast frequencies. Beta dominant activity appeared first in the left hemisphere from frontal to occipital channels (Fig. 7,*C*). There were periods of uniformity of frequency, amplitude and wave form in all channels.

EEG response to stimulation

Meditation brought about particular responses to flash and click stimuli administered to seven subjects during different stages of the practice.

(1) In accordance with the findings of Anand *et al.* (1961), during the alpha periods there was usually no alpha blocking.

(2) Click stimulation blocked the rhythmic theta frequencies of meditation, but they reappeared spontaneously within a few seconds

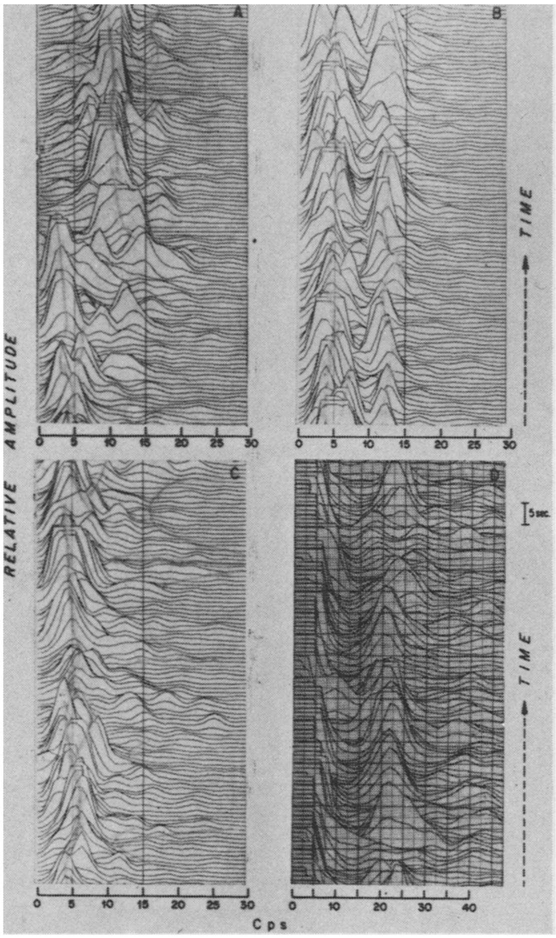

Fig. 5. Spectral arrays from derivation O1 during meditation. *A*, *B*, *C* from the same meditator. *A*: The picture shows the end of a theta train, a transition period and the beginning of an alpha train of high voltage; the spectral array comes from the end of meditation. The alpha train at that beginning of meditation is similar, with usually smaller amplitude. *B*: Transition phase between first and second stages of meditation with simultaneous presence of alpha and theta frequencies. *C*: Second stage of meditation showing a long train of 5 c/sec theta rhythm. *D*: Third stage of meditation. The vertical calibration has been increased to make more apparent the 20–25 c/sec beta rhythm, associated with slow frequencies and fast activity around 40 c/sec.

less than 1–2 or 3 sec), whereas the drowsy pattern was displaced into the alpha activity of an arousal reaction.

(3) During the deep meditation stages of low mixed frequencies and fast frequencies, there was no change in the electrical pattern (Fig. 4,*D*).

Muscle activity

Das and Gastaut (1957), using needle electrode recording of the tonic EMG, found complete disappearance of muscle activity during deep meditation. Our paper records from submental muscle areas showed the same trend, and muscle artifacts appearing like fast frequencies of large amplitude on the spectral arrays disappeared early during meditation.

Involuntary movements similar to those of early sleep could occur at the beginning of meditation, but disappeared in the deep phase. Eye movements recorded with the frontal electrodes varied in time: REMs of the beginning of meditation shifted early to slow eye movements. In deep meditation there was no eye movement. At the same time breathing became very slow and shallow. An occasional burst of rapid eye movements, similar to dream REMs, was related by the subjects to the occurrence of kaleidoscopic visual activity.

Voluntary movement (proper use of the signal) could be performed at any stage of meditation, testifying to the wakefulness of the subject. This performance did not alter the brain wave pattern of deep meditation (Fig. 4,*E*). The subjects could also answer any question readily and accurately.

DISCUSSION

The main EEG alterations must be compared with those of other states of consciousness in an attempt to individualize the meditative state.

(1) The dramatic increase in alpha abundance is not particular to meditation, since such techniques as operant control of the brain waves produce the same results (Kamiya 1969). More unusual is the ability of the meditators to maintain alpha activity after the end of meditation with eyes open, as well as the diffusion of large amplitude alpha waves to anterior regions.

(2) The strong propensity to slow frequencies in stage 2 of meditation must be differentiated from drowsiness and sleep. The main argument comes from the response to stimuli; the rhythmic theta trains of stage 2 were blocked by click stimuli but reappeared spontaneously within a few seconds. The usual drowsy pattern was changed into the alpha rhythm of an arousal reaction; therefore the rhythmic theta train of

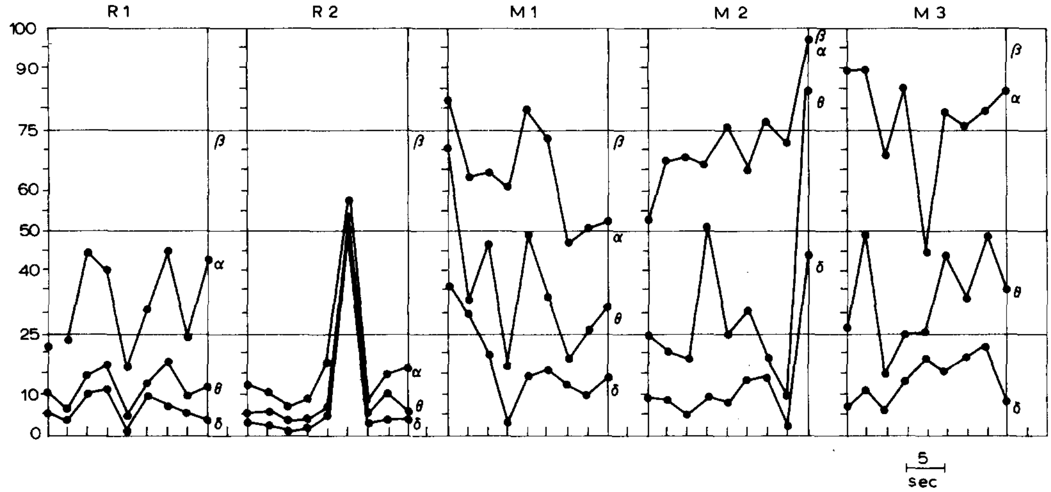

Fig. 6. Plots of the integrals of EEG amplitudes over the 4 different frequency bands: delta 0–3, theta 4–7, alpha 8–14, beta and fast frequencies 15–50 c/sec. X axis = time in 2.5 sec units. Y axis = relative abundance of each frequency band in % of the total. Each line is an upper boundary for the surface below and also the lower boundary for the area above. Delta and beta bands have the horizontal axis for outer boundaries. The areas between lines (not between lines and X axis) are the surface of integration of each frequency band, proportional to their abundance. *R 1*: Control subject during relaxation. The presence of alpha activity locates him in the alpha plus group. *R 2*: Control subject with almost no alpha activity. The isolated delta peak at the middle of the figure is rather an artefact (movement) than a period of drowsiness. *M 1*: Meditator in the relaxation phase just prior to meditation. Notice the greater amount of alpha and theta frequency than in the controls. *M 2*: Same subject during the first phase of meditation. The alpha band expands first, then slow activity increases dramatically and its beta band decreases. *M 3*: Same subject after meditation, during the concentration period. There is an important alpha remanence and a beta peak at the middle of the figure. The relative amounts of the different frequencies in meditators keep some stability during the change from meditation to other states of consciousness.

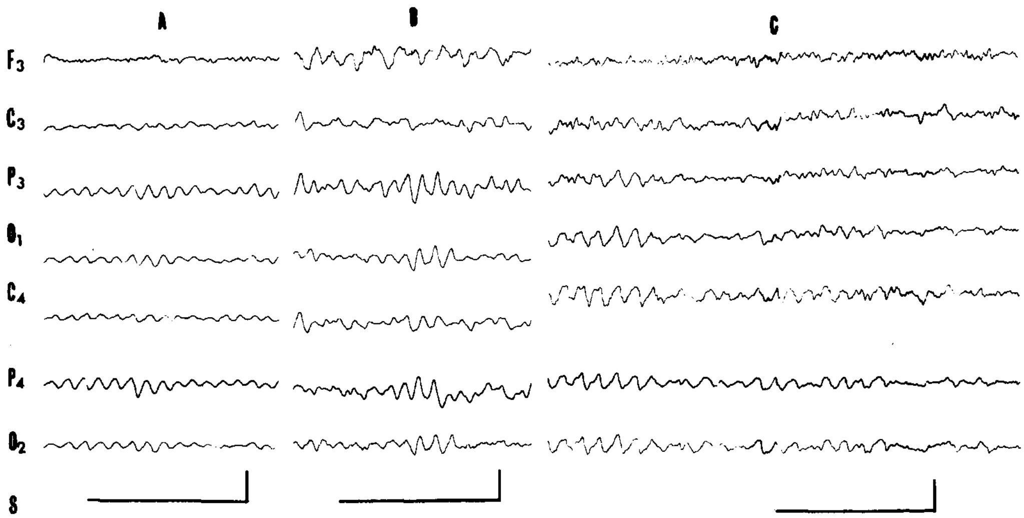

Fig. 7. *A* and *B* are from the same record at different moments of meditation. In *B* we see the increase of alpha amplitude in the different channels, and the appearance of alpha waves in F3. *C* represents the shift from alpha to beta dominant disorganized pattern. The change occurs successively in F3, C3, P3, O1 on the left and then on the right.

meditation has a reactivity similar to the waking alpha rhythm (Brazier 1968). The spectral analysis showed a morphological difference: meditation theta rhythms are continuous trains of dominant theta activity at a constant frequency (Fig. 5,*B*,*C*). Drowsiness produces a mixture or alternation of alpha, low delta and discontinuous theta frequencies (Fig. 1,*B*,*C*,*D*). Finally, theta waves can persist in the post-meditation period, with eyes open. Short bursts of large amplitude delta waves identical to those of sleep stage 4 could occur during meditation. In advanced subjects a simultaneous alpha rhythm deeply indented the curves of the delta waves; and this same pattern was found during deep night sleep.

The third important distinction is between the activating pattern of low voltage fast activity of the awake subject and that of deep meditation. On the ink-written record the beta rhythm of deep meditation appears on a background of slow frequencies; it has a spindle-like amplitude modulation (Fig. 4,*A*,*B*,*C*). Spectral analysis shows rhythmic fast frequencies around 20 and 40 c/sec. The activation pattern of the control subjects consists of dominant fast frequencies without any rhythmicity or regularity (Fig. 1,*A*).

These self-induced changes during meditation are of special interest inasmuch as they are not produced by other techniques like autosuggestion and hypnosis (Kasamatsu and Hirai 1966). Their neurophysiological interpretation could be based on three consistent findings of the deep meditation state: absence or decrease of EEG reaction to stimulation, even if the subject perceives external and internal stimuli; simultaneous persistence of an alert state of consciousness, allowing the subject to memorize and answer questions; possibility of voluntary movement without any noticeable modification of the brain wave pattern of deep meditation. We must deduce, therefore, that the EEG changes of meditation are independent of the interaction between the subject and the outer world but produced by the specific mental activity of the practice. The initiation of a loop between cortex, thalamo-cortical coordinating system and subcortical rhythm generators (Andersen and Andersson 1968) could account for the different alterations.

SUMMARY

Classical EEG combined with spectral analysis was performed on a group of subjects during Transcendental Meditation (TM). The findings were compared with those obtained in a resting control group.

(1) Alpha rhythm increased in amplitude, slowed down in frequency and extended to anterior channels at the beginning of meditation.

(2) In a second stage, theta frequencies different from those of sleep diffused from frontal to posterior channels. They took the form of short theta periods or longer rhythmic theta trains.

(3) Rhythmic amplitude-modulated beta waves were present over the whole scalp in a third stage of deep meditation by advanced subjects.

(4) The most striking topographical alteration was the synchronisation of anterior and posterior channels.

Therefore EEG records from meditators practising TM distinguish the meditative state from other states of consciousness. The combination of sequential EEG changes in relation to topographical alterations produces a particular pattern.

RESUME

ANALYSE SPECTRALE DE L'EEG DE L'ETAT DE MEDITATION

Une étude électroencéphalographique classique combinée avec analyse spectrale a été réalisée sur un groupe de sujets pratiquant la Méditation Transcendentale (MT). Les résultats ont été comparés avec ceux d'un groupe de contrôle en état de relaxation.

(1) Le rythme alpha s'amplifia, diminua de fréquence et diffusa vers les dérivations antérieures en début de méditation.

(2) Dans une seconde phase des fréquences thêta différentes de celles observées dans le sommeil s'étendirent de la région frontale aux dérivations postérieures, sous la forme de courtes périodes thêta ou de long trains d'ondes rythmiques.

(3) Des fréquences bêta à amplitude modulée en fuseaux, de fréquence fixe étaient rencontrées sur tout le scalp dans une troisième phase de méditation profonde, chez les sujets avancés.

(4) Les modifications topographiques les plus frappantes constituaient un phénomène de synchronisation entre les dérivations antérieures et postérieures.

Ainsi l'EEG des sujets pratiquant MT permet d'individualiser un état différent des autres états de conscience. Des modifications séquentielles de l'EEG combinées à des changements liés à la topographie de l'enregistrement produisent un type particulier de tracé.

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