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The History and Principles of Stereo EEG

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THE PRESTEREO EEG ERA

Stereoelectroencephalography (SEEG) was invented in the late 50s by Jean Talairach, a neurosurgeon, and Jean Bancaud, a neuropsychiatrist and electroencephalographer.[1] This method was based upon recording of brain electrical activity by intracerebral electrodes, stereotactically implanted in preidentified cortical and subcortical structures. When the technique was developed only electrocorticography (ECoG) was utilized. ECoG was an interictal investigation that did not provide any information on actual seizure onset. Furthermore, ECoG had to be carried out after craniotomy, so the decision of whether and how to operate had to be made at the same time in the operating room. In contrast, SEEG offered a method that allowed the investigative presurgical and therapeutic surgical stages to be separated. Using data from ictal and interictal EEG recordings, complemented with the results of local electrical stimulation applied through adjacent contacts of the implanted electrodes, surgical planning could be rationally prepared.[2]

The impetus for Bancaud and Talairach to start an epilepsy surgery program can be traced back to Henry Hécaen, a neuropsychologist who visited the Montreal Neurological Institute (MNI) and examined postsurgical patients with Wilder Penfield and Brenda Milner. After a year of study in 1952, Hécaen returned to Hospital Sainte-Anne, Paris, full of enthusiasm for surgical treatment of epilepsy. He convinced Gabriel Mazars, a neurosurgeon, that he should not wait to start an epilepsy surgery program based on the MNI method. At that time, Jean Talairach worked in the Department of Neurosurgery at the same hospital with his mentor Marcel David.[3] Since 1946 he had been developing stereotactic approaches to functional neurosurgery for chronic pain and movement disorders.[4] Jean Bancaud was a pupil of Henri Fischgold and had presented a doctoral thesis on the relationship between neuropsychological deficits and EEG features in patients with cerebral tumors. Then Fischgold's group joined David's in Sainte-Anne. Bancaud and Talairach met. They were instantly immersed in an outstanding medical and scientific environment, they were Mr. and Mrs. Dell in neurophysiology, H. Hécaen and J. de Ajurriaguera in neuropsychology.

Sainte-Anne was a psychiatric hospital founded in 1651. In the 50s, the department of psychiatry was dynamic and renowned as a pioneer group in biological psychiatry: Jean Delay, Pierre Deniker, with Henri Laborit demonstrated the "neuroleptic" effects of chlorpromazine in 1952. Hécaen had clearly a strong influence on Bancaud, who absorbed the lessons of Penfield on localization, and understood at a very early stage the complementary information provided

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by clinical signs and symptoms and the EEG, whether due to lesions or occurring during seizures. This insight led him to look for methods more accurate than ECoG for localization.

LAYING THE FOUNDATION

Meanwhile, Talairach was coming to a decisive turning point in his own methodological process. He had worked on the design of a surgical frame that would fit human brains of various sizes and would allow accurate repositioning. In 1947, the Talairach frame was born and improved over the years. Obsessed by increasing the accuracy of stereotaxic localization of deep structures, Talairach had also invented in 1949 the double grid system, a device made of two parallels grids attached to the stereotaxic frame, and through which locator needles or electrodes could be guided into the brain (Figure 1.1). The double grids served to minimize distortion due to X-ray diffraction in ventriculography images and thus offered the opportunity to precisely align radiological and postmortem anatomical data. Note that to further reduce distortion, Talairach later conceived a very large surgery room so that the X-ray tube was placed almost 5 m away from the grids.[2]

His vision was at that time very unusual. He regarded stereotactic methods as optimal for analysis of human brain anatomy in three-dimensional space, rather than as merely an instrument for reaching a target in the brain. Talairach built up a coordinate system based on the anterior commissure (AC) to posterior commissure (PC) base line and studied human neuroanatomy in reference to this line. This method also allowed the "normalization" of anatomical data from different brains such that data from the functional investigations of different patients could be displayed on the same summarizing chart. This enormous body of work led to the publication of two anatomical atlases. The stereotaxic frame, the double grids, and the AC–PC system were put together by Talairach to precisely map the anatomic stereotaxy of basal ganglia. In 1957 he published the first stereotaxic atlas of basal ganglia,[5] a book that soon became a reference for neurophysiologists and neurosurgeons. It took Talairach 10 years more to extend the stereotaxic approach to the entire brain. For this, he implemented the concept of proportional scaling to account for differences in brain size in the three directions of the AC–PC system. Working with a rare tenacity, he validated the concept in tens of postmortem studies and published in 1967 a second stereotaxic atlas devoted to the telencephalon, which also became a reference and a basis for SEEG.[6]

Bancaud became more and more attracted to Talairach's method, which promised to localize the sources of scalp EEG discharges. However, at that time, stereotaxy was oriented toward pain, dyskinesias, parkinsonian tremor, and some otherwise inoperable tumors. Working with M. B. Dell, Bancaud got progressively convinced of the clinical utility of epilepsy surgery but considered that methods of investigation current at that time were poorly adapted to epileptic phenomena.[7]

After Talairach's completion of the 1957 anatomical atlas, Marcel David took Talairach's views into account and supported a project to create an operating room dedicated to stereotactic surgery. This theater needed to be large enough to satisfy the physical requirements of teleradiography and allow parallel X-ray beams in order to avoid distortions of skull, vessels, ventricles, and, crucially, the frame and double grids used for guiding the placement of intracranial electrodes. The concept of a stereotactic surgery room was born, and such a suite was opened in Sainte-Anne in 1959 in the walls of an ancient chapel. Bancaud saw the potential of a spatial conceptualization of the human brain promoted by Talairach's method and began working with him to develop applications of stereotactic functional exploration to presurgical investigations of intractable epilepsies. In the minds of Talairach and Bancaud, Penfield's localization approach could be thoroughly applied only through electrophysiological recording of seizures directly from the involved brain structures. This goal was achieved in 1959 using Talairach's stereotactic method to accurately place intracerebral electrodes with respect

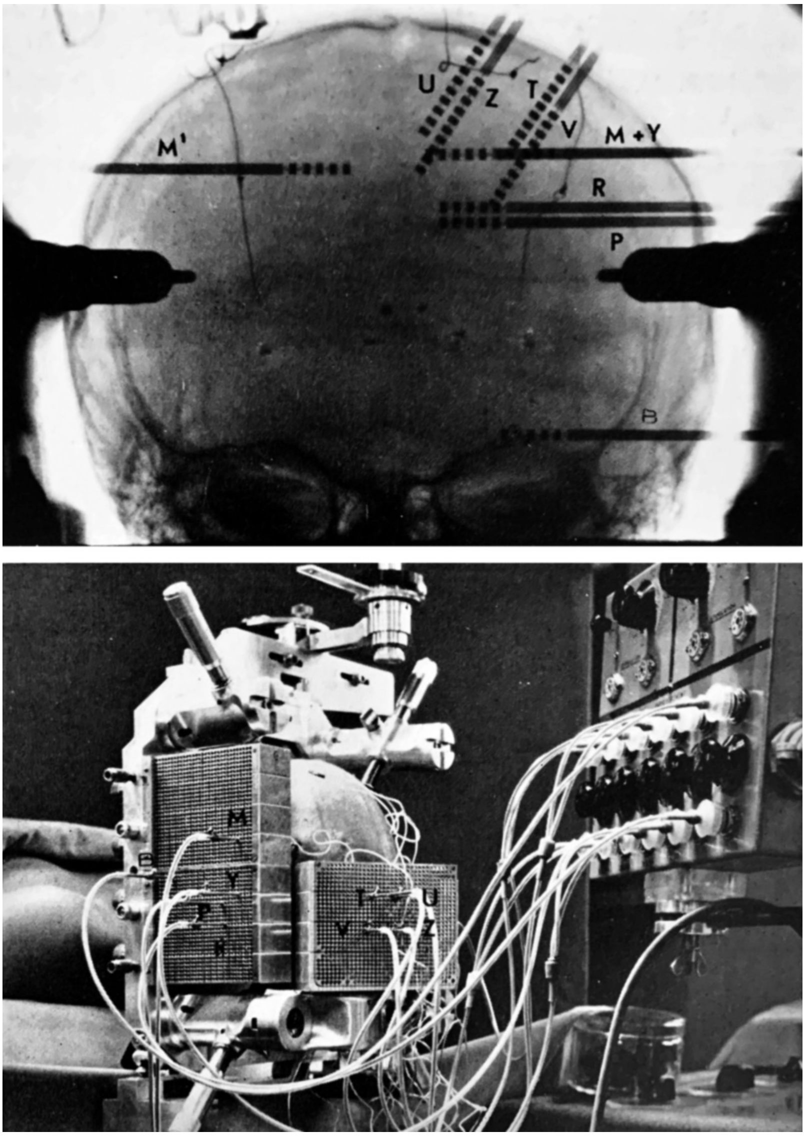

FIGURE 1.1 The Talairach stereotaxic frame with the double grids allowing orthogonal and oblique electrodes implantation (circa 1962).

to reliable anatomical markers and then record the electrical activity of multiple cerebral structures during the course of a seizure.

Benefiting from this extraordinary technical achievement, Bancaud developed a careful analysis of anatomical–physiological–clinical correlations that could directly determine surgical strategy by utilizing electrophysiological recordings of seizures precisely localized in cerebral space. With these data, Bancaud studied the spatiotemporal dynamics of seizure discharges with respect to their clinical features. In particular, he first described the respective contributions of medial and lateral cortical areas in the organization of temporal and frontal seizures: the role of amygdala and hippocampus versus the temporal neocortex in temporal seizures (Figure 1.2),[8,34] and the role of supplementary motor area and cingulate area 24 versus the dorsolateral, ventrolateral, and ventromedial frontal cortices.[9] These studies had immediate repercussion on the practice of epilepsy surgery.

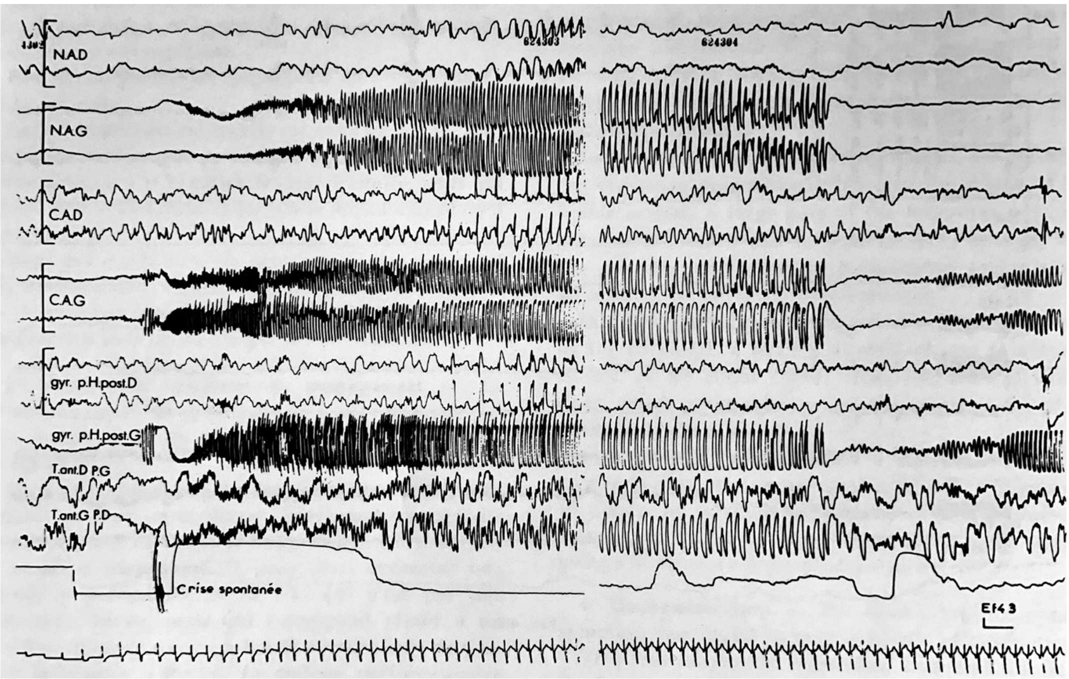

FIGURE 1.2 Stereo EEG recording in temporal lobe epilepsy circa 1962. Seizure onset with a fast activity in left amygdala (NAG) and left hippocampus (CAG) spreading to the posterior parahippocampal gyrus (gyr pH post G). The two bottom traces are scalp EEG, that was simultaneously recorded.

CONCEPTUALIZATION OF STEREO EEG

Intracerebral ictal recordings provided data so complex that their interpretation needed a strategic roadmap. The designations of the cortical areas according to their hierarchical involvement in the epileptogenic process required precise definitions. The region where seizures originate was obviously in the forefront of presurgical planning. The "epileptogenic zone" was differentiated from the space occupied by interictal activity, or the "irritative zone," and from the space occupied by any morphological alteration or lesion supposed to be related to the epilepsy, or the "lesional zone." Talairach and Bancaud showed that the lesional and irritative zones had a variable topographic relationship with the epileptogenic zone.[10] Talairach and Bancaud developed a new type of epilepsy surgery, based on a three-dimensional representation of the epileptogenic, irritative, and lesional zones. With this novel method, the surgical plan could be carefully prepared and adapted to the individual patient's case by referring radiological, physiological, and clinical data by physical matching to the same patient through the stereotaxic method.

The epileptogenic and lesional zones' relationship depending on their cortical localization and on the different types of lesions underwent ongoing evaluation and validation. Today the use of neuroimaging has simplified the question of the lesional zone. At that time, only pneumoencephalography, lipiodol ventriculography, and cerebral angiography were available. Talairach looked for localizing and then operating responsible lesions with the help of localizing the epileptogenic zone. SEEG was so precise that he discovered numerous pseudotumoral, nonexpansive lesions (they would be identified later as dysembryoplastic neuroepithelial tumor and cortical malformations) that had not been previously shown by the neuroradiological techniques. He therefore encouraged Bancaud to find electrical criteria for detecting lesions. In SEEG terminology, the term "lesional zone" referred to the area occupied by various types of slow-wave activity (characterized by waveform, frequency, and reactivity). The correlations were clearly superior to those given by the available neuroradiological images. Talairach and Bancaud, using the SEEG method, extended its application to map better the extent and anatomical location of astrocytomas or oligodendrocytomas. They correlated SEEG findings with the results of stereotaxic biopsies.[11] According to histopathology, surgical resections avoiding functional deficits or targeting stereotactic interstitial radiotherapy could be preplanned. The topographic transitions between electrical silence inside glial tumors, slow waves, spiking, subclinical paroxysms, and seizure activity were analyzed. Beyond their clinical utility for tumor surgery, all this collection of anatomical-electrical data served as a model to interpret SEEG in cases of epilepsy. Definitions were less precise for the cortical areas producing interictal spikes and ictal discharges. When Bancaud began to record seizures using intracerebral electrodes, he noticed that the respective topography of the two types of discharge, interictal and ictal, were far from fully overlapping. He therefore used the terms "irritative zone" and "epileptogenic zone" to describe and differentiate the spatial extent of interictal spiking and ictal discharges respectively. The term epileptogenic zone thus referred to the anatomical structure(s) where primary organization of seizures took place.[12] The role of fast synchronizing discharges that might involve more often distinct but interconnected regions than a single region was emphasized.

Even though they could not give it a scientific content, the concept of epileptogenic zone was central to the development of SEEG. Bancaud and Talairach were immediately convinced to use it as the basis of their surgical strategy rather than the location of interictal discharges used by Penfield. Since the seizure was the symptom to be cured, it was the area of seizure organization that had to be determined. However, a strict correlation between the area(s) of seizure onset and emergence of clinical semiology was often difficult to establish in practice, because ictal signs and symptoms appeared and overlapped in time as the ictal discharge propagated to different cerebral structures. Understanding the spatiotemporal dynamics of the seizure as revealed by the sequence of signs allowed Bancaud to elaborate an extrapolation of its anatomical origin. This was a genial intuition. With this principle of extrapolation, the characterization of the initial symptom(s) or sign(s) appeared to be no more important than any later part of the seizure. Bancaud's seizure patterns included order and sequence of semiological elements as their crucial features and were always referred to anatomy.[13]

Bancaud and Talairach definitely regarded a static view of seizure genesis represented by the gross topography of interictal and/or ictal onset abnormalities as insufficient for determining the area and volume of brain tissue to resect. They believed that a dynamic model of the discharge should be inferred from detailed consideration of all the data giving good discrimination between pacemakers versus active and passive relays of propagation. This was a prerequisite for surgical therapy in order to remove the smallest possible volume, and an intellectual discipline able to provide sound outcome information for further refinement of surgical criteria. With time the novel technique of Bancaud and Talairach evolved into a comprehensive and established method, where electrophysiological advances increased knowledge of anatomo-functional correlations giving rise to the beginnings of the functional exploration of networks.

TECHNICAL REQUIREMENTS

Fixating double grids onto the stereotactic frame ensured safe implantation of intracerebral electrodes recording from lateral and medial areas of the cerebral cortex. Safety was further guaranteed by routine stereotactic angiography, allowing electrode placement that avoided vulnerable blood vessels. The practice of stereotactic angiography was associated with a very low risk. The stereotactic atlas of the telencephalon, containing frontal, axial, and sagittal brain slices referenced to the AC–PC baseline, was used as a guide to the topography of cortical areas. The Talairach grid system based on AC–PC provided a statistical representation of the spatial distribution of cortical sulci. The accuracy of this approach was satisfactory for designing electrode implantations or for comparing patients but was insufficient for detailed interpretation of an individual patient's SEEG data. A reconstruction of the precise position of the electrode contacts after implantation relative to the individual patient's anatomy was still necessary. Fortunately, Gabor Szikla had taken advantage of the need for stereotactic angiography and had carefully described cerebral cortical blood vessels and their close relationships to the convolutions of gyri and sulci. He showed that cortical vessels mold themselves to the form of the gyri. He was able to extract gyral form and dimensions from a meticulous analysis of vascular anatomy. This discovery led to the concept that "vascular lamina" could provide constant landmarks for interpretation of anatomical variability among individuals and turned out to be a very precise tool for deducing the actual location of electrode contacts before the availability of modern imaging methods.[14]

The anatomical method of Talairach has not only survived the development of magnetic resonance-derived stereotactic techniques but continues to be the referential basis for SEEG.[15]

FROM COMPREHENSIVE BRAIN SAMPLING TO RATIONAL SURGERY

SEEG offered high spatial and temporal resolution and a high power of localization. This was immediately evident in the early 1960s when the role of amygdala and hippocampus in temporal lobe seizures was discovered.[16] During the next decade a major pitfall was to confuse stereotactic depth electrode explorations and real SEEG. This former type of implantation could be targeted for instance to preselected sites thought to be the source of paroxysmal activity on the basis of empirical arguments. This could be bilateral and symmetrical electrodes in mesial temporal structures only in cases of temporal lobe epilepsy. In contrast, SEEG is displaying the spatiotemporal dynamics of seizures in relation to the anatomy. This was contingent on using multiple multilead electrodes to give a distribution of spatial sampling sufficient to capture as much of the paroxysmal activity associated with the seizure as possible. A too compartmentalized or restricted view of ictal intracerebral activity would be insufficient to understand correlations with clinical semiology.

The essential question of reliable spatial sampling was whether recording from too restricted a brain area would prevent SEEG from providing an accurate view of the electrical organization of the entire epileptogenic zone. An ideal distribution of sites for intracerebral recordings provides the neurophysiologist with an immediate view of the dynamics of ictal and interictal events. Physiological interpolation between the recording sites would thus depend on a correct strategy of implantation, which requires that the implantation be managed within a coherent method based on the individual patient's symptoms. In this context, a strategy of electrode implantation demands a clear hypothetical framework regarding the distribution of the epileptogenic and lesional zones derived from a detailed analysis of the electrophysiological features of the interictal state, the video-EEG electrical–clinical correlations of the ictal state, and their relation to anatomical anomalies. SEEG was conceived for its capability to validate or invalidate a principal hypothesis, and at the same time to support or eliminate an alternative hypothesis.

This "anatomo-electro-clinical" method produced types of data sets that may interact and validate one another. For example, the coincidence of clinical and electrical onset, or the precedence of electrical onset to clinical onset, both tend to confirm accurate positioning of a recording electrode. An indispensable tool is provided by intracerebral stimulation through stereotactically implanted electrodes, a technique proven reliable for showing the relationships between the different involved areas and the ictal semiology. Electrical stimulation can confirm topography of the ictal onset by provoking a habitual seizure and gives useful insight into the organization of the epileptogenic zone, by separating relay and subrelay areas essential for building up individual ictal symptoms and signs, as well as their modes of clustering. Such data are helpful to the surgeon in planning a strategy of removal and/or disconnection.

The ultimate objective of SEEG is to provide the surgeon with an integrated view of the epileptogenic process, based on the definition of the epileptogenic zone and its overlap with the lesional zone. Eventual matching of clinical, physiological, and anatomical data is essential, and the role of this stereotactic method in preoperative planning is exactly to achieve this objective. During surgery, anatomical and physiological data that describe the epilepsy and the function of related cortical areas are referenced to three-dimensional coordinates, which allows the surgeon to perform a comprehensively preplanned cortectomy within predetermined functional and vascular constraints.

THE STEREO EEG SCRIPTURES

The development of SEEG ushered in a new era that coincided with a complete structural reorganization of the Sainte-Anne Department of Neurosurgery. Alain Bonis, a neurologist and pupil of Raymond Garcin, joined the team, completed by Gabor Szikla, an emigrant from Hungary in 1956, who was to devote his career to anatomy and stereotactic surgery under Jean Talairach. In 1960, David and Fischgold moved away to La Pitié-Salpétriere, and Talairach became the head of a new Department of Functional Neurosurgery at Hospital Sainte-Anne.

This was a period of scientific productivity. The role of temporal limbic structures, the amygdala, and the hippocampus in clinical symptomatology and electroclinical organization of temporal lobe seizures was demonstrated. Clinical manifestations of absences that had been attributed to discharge of "centrencephalic" nuclei and as such considered as signs of generalized epilepsies by Penfield, Gastaut, and others could be elicited by stimulation of frontal anterior and intermediate areas, especially from their medial aspect.[17] The anatomical-functional organization of the supplementary motor area was described as a part of the premotor systems and considered distinct from language areas.[18]

The first milestone in the establishment of SEEG fundamentals was the book *La Stéréoelectroencéphalographie dans l'Épilepsie* published in 1965.[19] A modern and dynamic view of the focal epilepsies emerged from the observations, reflections, and discussions it collected. This book marked a break with the past, and, beyond the specific questions it raised in the field of epilepsy surgery, it provided an authoritative justification of the critical necessity for studying seizures when studying epilepsy.

SEEG offered the opportunity of analyzing the dynamics of epileptic phenomena in humans, but also represented a remarkable tool for the study of normal neurophysiology. Pierre Buser, a prominent neurophysiologist interested in the cerebral cortex, undertook such studies in cooperation with Bancaud after 1964. He worked on motor systems, particularly the pyramidal system and sensory polymodal afferents to the frontal cortex. One of the models he used was the startle reaction in the anesthetized cat. This led to a better understanding of startle physiology, and the startle epilepsies in hemiplegic children being investigated by Bancaud.[20] Buser influenced Bancaud's work on various aspects of epilepsies with motor manifestations. Besides the startle epilepsies, they worked on the connections of the supplementary motor area,[21] and together demonstrated the cortical origin of myoclonus and seizures in the Kojevnikov's syndrome or epilepsia partialis continua,[22] as well as the cortical origin of postanoxic action myoclonus (Lance and Adams syndrome).[23] Buser used SEEG not only for functional mapping, but also to study corticocortical connections and their facilitation inside the epileptogenic zone.[24] He was the first to use single pulse electrical stimulation to explore the excitability of corticocortical pathways and was in fact the pioneer of the technique named cortico-cortical evoked potentials (CCEPs) some 30 years later.[25] These anatomical and physiological advances eventually convinced Talairach that he should add a significant section on SEEG and neurophysiology to his stereotactic anatomical atlas of the telencephalon in 1967.[6]

The Institut National de la Santé et de la Recherche Médicale Research Unit entitled "Stereotaxic Functional Exploration and Surgical Treatment of the Epilepsies" headed by Talairach was created in 1970. This new facility helped Bancaud to approach some basic problems in the electrophysiological investigation of the human epilepsies and set new trends in the characterization of frontal lobe seizures.

Bancaud and Talairach paid more attention and invested much more time to write books than journal articles. They considered that the challenge posed by human intracerebral recordings, the new concepts on epilepsies they were generating, and their consequences for surgical strategy were so complex that they could not be thoroughly described and properly discussed in a limited article format. They had themselves been inspired by the detailed clinical experience handed on from their predecessors. As a matter of proof, at the end of my first interview with Bancaud in 1971, I was given the five books of Penfield to read before getting back to him.

In the same period, Bancaud returned to the questions of scalp EEG interpretation raised in his doctoral thesis and clarified many of them on the basis of data accumulated from comparisons between EEG and SEEG. The 1973 book *EEG et SEEG dans les Tumeurs Cérébrales et l'Épilepsie* was especially dedicated to electroencephalographers and collected unique and important data on simultaneous recordings of EEG and SEEG during numerous investigations of cerebral tumors and epilepsies in the stereotaxy "chapel." Nowadays, it remains a valuable and useful guide to understanding what we record and what we miss in surface recordings of slow waves, spikes, and seizures.[26]

Between 1970 and 1973, with the help of Stéphane Geier, the recording period of SEEG lengthened, and from "acute," SEEG became "chronic." Technically speaking, intracerebral electrodes were significantly reduced in size and adapted to the new mode of recording while the patient was freely moving. Telemetry was used, as well as video-recording with EEG and video signals being retrospectively matched.[27] These new types of recording out of the operating room allowed a much better study of gestural automatic behavior that characterize certain complex partial seizures. In particular gestural manifestations, correlated with anterior frontal lobe paroxysmal discharges, were identified.[28] Their phenomenology, duration, and mode of association differentiated them from gestural automatisms of temporal lobe origin.[29] Some observations made at this time suggested an epileptogenic zone distributed between frontal and temporal lobe areas, leading to the concept of frontotemporal epilepsy, and to a concomitant change in surgical strategy. In the search for mechanisms of "automatisms," Bancaud and his coworkers reported the behavioral effects of anterior cingulate gyrus stimulation which essentially consisted of complex hand–mouth coordinated movements with mood alteration toward disinhibition.[9,30]

The continuing collaborative work of Jean Talairach and Jean Bancaud culminated in a global report presented in 1974 to the Société de Neurochirurgie de Langue Française, entitled "Approche Nouvelle de la Neurochirurgie de I'Epilepsie," and published as a supplement volume of the *Neurochirurgie* journal.[31] This presentation specified the successive and multidisciplinary steps of the method and made clear the importance of making the surgical operation fit the seizure semiology through a meticulous and rational correlative approach.

So remarkably extensive was the range of research and curiosity of Talairach and Bancaud that it is difficult to highlight the major elements of their scientific legacy. Surely one of their most important contributions is the emphasis they have placed on the value of clinical semiology and its integration through the "anatomo-electro-clinical correlations" of a patient's seizures. The body of work that has been produced from these principles has transformed what was at the beginning a technique of stereotactic functional exploration into a general method of studying a patient with epilepsy. In a sense, they have fashioned a tool that has turned out to be fundamental, as proven by the fact that it has survived the development of imaging and other noninvasive techniques.[32] Indeed, not only has it survived, but it has framed a preinvasive rationale for the current imaging techniques by providing a referential system perfectly suited to the investigation of this anatomo-functional crossroad.[33]

SUMMARY

A serendipitous encounter between Jean Talairach and Jean Bancaud in the late 50s marked the origins of a new conception in presurgical exploration of epilepsy. They named it stereoelectroencephalography or SEEG, meaning that it was based on a multidimensional (supplied by stereotaxy) recording of multiple brain areas (through multilead depth electrodes) simultaneously. This novel method allowed for separating a presurgical localization from a surgical treatment phase. A closed skull setup enabled intracerebral seizure recording for the first time in a fully interacting patient. SEEG interpretation was based on ictal anatomo-electro-clinical correlations. A better comprehension of seizure build-up in the human brain led to major pathophysiological advances. SEEG-guided epilepsy surgery was performed only in Paris during the first 25 years, and then adopted in Switzerland and Canada. Ten years later, its practice developed in France (Rennes and Grenoble), and also in Italy (Milan). Its recent worldwide expansion confirms its universally recognized rationality and its perfect adjustment to brain imaging.

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Only key references appear in the print edition. The full reference list appears in the digital product found on http://connect.springerpub.com/content/book/978-0-8261-3693-0/part/part01/chapter/ch01

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