Analysis of EEG Signals in a Patient with Spastic Cerebral Palsy Undergone Dolphin-Assisted Therapies

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***Abstract*—Cerebral palsy is a group of developmental disorders that affects a certain percentage of population motivating the development of several types of therapies ranging from conventional where physical therapies are included to some *alternative therapies* such as the dolphin-assisted therapies (DAT), in order to improve the quality of life of patients suffering these disorders. To find scientific evidence of the DAT effectiveness, in this work is developed a four-stage first-order cybernetic model: i) Signal Acquisition, ii) EEG Processing, iii) EEG Exploring and iv) Healthcare Informatics System (HIS-DAT), in order to explore the electroencephalographic signals behavior from a patient with Infantile Spastic Cerebral Palsy undergone DAT, as well as bioacoustic signals emitted by a female bottlenose dolphin via specialized transducers or passive sensors for aquatic environments, by using nonlinear mathematical tools. We found that the Power Spectrum of signals from EEG and Hydrophone yield similar densities along all DAT and the child's brain activity increases 3-fold higher-frequency when the therapist-dolphin pair interacts with the patient. These findings are supported by the Self-Affine Analysis outcomes, pointing out the emergence of negative correlations from the patient's brain activity during the whole session of DAT but the greatest changes occurred During DAT.**

Keywords*—*Brain–computer interfaces; healthcare system; nonlinear dynamics; assisted therapies; infantile spastic cerebral palsy; analysis of EEG signals; power spectrum; self-affine analysis

I. Introduction

Artificial intelligence (AI) generally is entitled with the development of techniques and devices to perform tasks that involve human interpretation and decision-making. Recently has raised many advances in medical AI applications owing the substantially enhanced computing power of modern computers and the vast amount of digital data available for collection and utilization. AI technologies can ingest, analyze, and report large volumes of data across different modalities to detect disease and guide clinical decisions for health services management and patient care treatments [1]. For instance, in [2] processed electroencephalography (EEG) signals to detecting emotional states tested the effects of meditation music therapy to stabilize mental states in groups of three to anger, calmness, happiness and sadness. They collected 120 emotion signals by using an Emotive 14-channel EEG headset. Therefore, tools developed in AI can be applied to measure and evaluate the effectiveness of therapies carried out to improve the life-quality of patients suffering one or several developmental disorders, based on EEG signals collected from the patients' brain activity undergone assisted therapies.

Cerebral palsy is a group of developmental disorders diagnosed by their disturbance of the subject's movement and posture, caused by early nonprogressive lesions of the central nervous system [3]. In 1862, William Little connected this disorder to a lack of oxygen during birth and described it as a disorder that appeared to strike children in the first year of life, affected developmental skill progression, and did not improve over time. In 1897, Sigmund Freud suggested that cerebral palsy might be rooted in the brain's development in the womb and related aberrant development to factors influencing the developing fetus. Birth asphyxia alone was thought to be the cause of cerebral palsy until the 1980s, when biomedical research found this etiology to be less likely and only one of many with potential to result in cerebral palsy [4].

Cerebral palsy can be defined according to the anatomical site of the brain lesion (cerebral cortex, pyramidal tract, extrapyramidal system, or cerebellum); clinical symptoms and signs (spasticity, dyskinesia [dystonic and choreo-athetotic forms], or ataxia); topographical involvement of extremities (diplegia, quadriplegia, or hemiplegia); timing of presumed insult (prepartum, intrapartum, or postneonatal); and classification of degree of muscle tone (isotonic, hypotonic, or hypertonic) [5], [6].

The main symptoms of cerebral palsy are disorders of movement and posture, but more recently other symptoms have been included in the definition: disturbances of sensation and perception, global or specific cognitive difficulties, communication disorders, behavioral disorders, and seizures [3], [7]. There is no cure for this lifetime condition, but therapy, education, and technology can maximize each child's potential by improving functional abilities and quality of life.

The diagnosis of cerebral palsy is made largely through clinical observations, whose major signs collectively can identify delayed motor milestones, abnormal neurologic examination, persistence of primitive reflexes, and abnormal postural reactions [4]. The Gross Motor Functional Classification System was developed by Rosenbaum and collaborators in 2002 to help professionals anticipate gross motor abilities and severity of cerebral palsy, according to five levels: Level I: able to walk without restrictions; Level II: able to walk without devices; Level III: able to walk with mobility devices; Level IV: self-mobility with limitations; and Level V: self-mobility severely limited [4], [8].

More than 50% of children with cerebral palsy and mental retardation suffer from epilepsy, mostly revealed in the first 4–5 years of life. Epilepsy usually occurred in children with accompanying vision and hearing disorders, and the inability to walk [9]. Besides, children with cerebral palsy often have the following disorders: irregular sleep patterns, lower urinary tract dysfunction, gastrointestinal disorders, drooling, aspiration, swallowing, osteoporosis, malnutrition, inadequate growth, gastroesophageal reflux, impaired language skills or cognitive limitations, among others [10].

Spasticity refers some degree of loss of motor control, abnormal tone, and weakness, which commonly can lead to contractures, scoliosis, and hip subluxation or dislocation. The child with cerebral palsy needs frequent position changes and needs to be out of his or her bed and/or wheelchair frequently at home and at school. Scoliosis may not only progress more rapidly but may continue after skeletal maturity occurs. Progressive hip adduction and flexion is also common, leading to femoral anteversion, subluxation, deformities of the femoral head, and hip dislocation, which can progress to degeneration, sometimes with pain [10].

Treatment of spasticity involves systematic rehabilitation, if necessary, assisted by pharmacotherapy, physiotherapy or surgical interventions, offering benefit, at least in the short term. Most physical therapies are based on the principles of neuroplasticity, patterning, postural balance, muscle strengthening, or stretching [9].

The total degree of overflow brain damage from the initial insult, may not be realized until the preschool or school age period. One of the most limiting comorbidities of cerebral palsy is mental retardation. Children with cerebral palsy that suffer mental retardation can have self-abusive behavior such as biting, head banging, or scratching. These behaviors may stem from anxiety that results from being unable to communicate needs such as hunger or pain. However, children with cerebral palsy who have normal intelligence may have some degree of coexisting visual perceptual abnormalities and learning disabilities that can affect overall development and learning. The assessment of intellectual functioning is often challenging in children with motor impairment because the majority of tests used require verbal and motor responses [10].

Confirming the diagnosis allows the family to plan for long-term treatments and management options that may be needed by the child. Having a diagnosis of cerebral palsy may qualify the child for increased insurance benefits, admission into handicapped preschool or school programs, and assistance in the form of federal assistance. The prediction of the future deficits or abilities at the time of diagnosis often is a *wait and see* situation [4].

Moreover, we want to highlight the importance of trying to improve the functional abilities and quality of life of children with cerebral palsy in developing countries owing. For instead, in [5] it argued that people with *Cerebral palsy* has a high risk for discrimination, neglect, and abuse, particularly those in rural settings owing low school attendance and lack to access to professional assistive. Indeed, individuals with cerebral palsy have a right not only to inclusion but also to full participation in society and pursuit of their hopes and aspirations.

There are several *alternative* therapies used by families to complement systematic rehabilitation (assisted by pharmacotherapy, physiotherapy or surgical interventions), in order to try to improve their children's quality of life. Although there is a little scientific evidence about the effectiveness of these therapies, for some parents it is essential to explore each and every possible intervention that may be available for their children. Regardless their effect, these alternative therapies may offer the parent a feeling of participation or control, but unfortunately they usually cost large sums of money. Some examples of these alternative therapies are the following: massage therapy, horse riding, hyperbaric oxygen, conductive education, patterning, transcutaneous electrical stimulation, chiropractic manipulation, or dolphin-assisted therapy [10].

Since 1971, the *alternative* therapies called dolphin-assisted therapies (DAT) have been proposed to try to improve the quality of life of patients suffering psychological and neurological disorders such as cerebral palsy [11], [12], including Infantile Spastic Cerebral Palsy. In these patients are manifested early nonprogressive lesions of their central nervous system produced during pregnancy, as well as a severe motor delay in the early stages of their development owing their brain undergoes changes in its structure and organization. Hence, these patients have difficulty making more precise movements such as taking a spoon or making a clamp with their fingers and they also lack muscle coordination in some movements.

DAT are based on interaction between live captive dolphins and patients who suffer from various conditions, and this kind of interaction is supervised for both the dolphin trainer and the child therapist. However, an important differentiator that highlights this sort of alternative therapies is the intelligence of these animals, described and being recognized since the development of the Minoan civilization in Greece (3000 BC and 200 BC), and being studied over the years by various researchers [13], [14]. Like in humans, the dolphins' brain is very big regarding their body, therefore communication between both species can be possible [15], [16], [17].

There is evidence [18], [19], [20] about the abilities of dolphins to learn simple tasks with greater efficiency than some primates, allowing to observe the dolphins' ability to transmit the acquired knowledge and complex behaviors learned to other members of their species even for generations [21], [22], [23]. Besides, dolphins have been able to modify their behavior to do the tasks in a more efficient way, showing their interest to be part of the assisted therapies [15], [24]. In part, these dolphin's capabilities make it a better candidate to be part of assisted therapies.

In summary, cerebral palsy affects a certain percentage of the population motivating the development of several types of therapies ranging from conventional wherein physical therapies are included to some *alternative therapies* assisted by animals such as DAT, in order to improve the quality of life of patients with these developmental disorders. To find scientific evidence of the effectiveness of DAT, in this work, based on information technologies, has been developed a Healthcare Informatics System (HIS-DAT), as the last stage of a four-stage first-order cybernetic model, to explore biosignals or biomarkers for measuring mainly quality of patient's medical care. Our HIS-DAT explores the behavior of electroencephalographic (EEG) signals in addition with bioacoustic signals by using nonlinear mathematical tools.

To look for scientific evidence from exploring EEG signals in a patient with Spastic Cerebral Palsy undergone DAT by means of our HIS-DAT, we make use of several tools from both computer science, in particular with parallel computational systems, and non-parametric or non-linear mathematical algorithms for the EEG-signal processing, in order to find emerging patterns at different time scales in the brain activity of a child with spastic cerebral palsy.

Therefore, this article is organized as follows. Section II describes our method designed to collect and process EEG signals. Section III presents the main results obtained after processing both bioacoustic and EEG biosignals. Section IV discusses the results obtained from both the Power Spectral Density and Self-Affine analysis in terms of changes detected in patient's brain Before, During and After DAT. Finally, Section V provides the authors' main thoughts.

II. Method

A. Case Study

During Dolphin-Assisted Therapies (DAT), the fundamental participants are therapist, dolphin's trainer, patient with Infantile Spastic Cerebral Palsy (ISCP) and female bottlenose dolphin. In this work, the cerebral activity of the patient with ISCP and dolphin are measured and explored to determine with scientific evidence the cause-effect correlation between them during DAT. It is worth emphasizing that only one child with ISCP was used as a case study, which we will refer to hereinafter as *Patient*. Characteristics to be taken into account for this research are following:

- Patient with ISCP: Analysis of the cerebral electric fields resulting from interaction between neurons during process of DAT.
- Female bottlenose dolphin: Bioacoustic signal emitted for communication between frequencies of 200 Hz and 150 kHz. Added to these the *clicks* emitted for its echolocation ranging 20 kHz to 150 kHz.

B. Signal Acquisition Tools

Electroencephalography measures the spontaneous electrical activity of the cerebral *cortex*, i.e. the surface layer of the brain. This phenomenon is not due to the simple addition of the action potentials of the 1×10^{11} neurons that make up the brain. The rhythmic variations in the observed waves owed a large population of neurons oscillating coherently. In other words, they all generate a signal of the same frequency. The presence of these rhythms indicates brain activity at the level of millions of neurons acting together synchronously. The form of the EEG signals depends on the age and alertness of patient, changing markedly during childhood. In a healthy brain, this activity is very similar in the different regions of the brain, so there will be no appreciable differences between the different areas of the cortex, called *lobes*. The real-time recording of brain electrical activity lacks a reproducible pattern, which resembles a *chaotic* signal of very small amplitude, around 10-100 µV so it is not difficult to confuse it with a random noise. For this reason, normally studies of the EEG signals focus on its power spectrum via an analysis in frequency bands, but we also introduce a fractal characterization [25] to find emerging patterns from a quantitative nonlinear point of view.

EEG signals are measured as a voltage difference between two electrodes. In order to be able to measure such a small signal, the contact between electrode and skin must be correct. Often the skin receives a preparatory treatment, namely oily skin and dead cells are removed from the surface to arrange a conductive gel or paste to improve contact, in order to measure the impedance between the electrode and the skin. To achieve correct results, the impedance should not be much above 5 $k\Omega$.

Usually there are two configurations for the placement of the electrodes: i) in a referential way and ii) in a bipolar way. The first one is also called *monopolar configuration*, the reference is the same for all electrodes, i.e. when two EEG signals are recorded with a 2-channel EEG module, two active and one reference electrodes would be needed in addition to the ground electrode. Whereas for *a bipolar configuration* each channel has its own reference, so that to record two signals, i.e. four electrodes are necessary in addition to the ground electrode. The ground electrode that is added in both configurations is intended to reduce the common mode, e.g. the annoying interference of the electrical network [26].

Generally an EEG signal is characterized by means of its power spectrum. Traditionally the spectrum of an EEG signal is divided into four frequency bands. Besides, an EEG signal is going to be made up of components from all bands to a greater or lesser extent, but under certain conditions one or the other prevails. An EEG signal can be described as follows:

1) δ Band (0.5-3.5 Hz): Low frequency and high intensity waves (a few hundred µV). They occur in young children and adults only in a state of deep sleep, unconsciousness or situations that increase intercranial pressure such as brain tumors.
2) θ Band (3.5-7.5 Hz): These waves of amplitude less than 20 µV occur during the maturation process in the entire cerebral cortex, although it predominates in the occipital and temporal region and is faster in the frontal area. There are prevailed in children 5-7 aged and are associated in adults and adolescents with creative thoughts, stress or psychic disorders.
3) α Band (7.5-12.5 Hz): These waves of amplitude less than 20 µV are known as *alpha rhythm* and are referred to bursts of 20-100 µV of amplitude and great periodicity at those frequencies predominant over the occipital region but appearing throughout brain cortex. Average frequency of the alpha rhythm in an adult population is about 10.2 Hz. These waves are also associated with states of relaxation, inactivity and are very evident in the absence of visual stimuli[27].
4) β Band (12.5-30 Hz): These small amplitude signals, below 20 µV, are quite common and predominate during adulthood. There are usually divided into low beta, medium beta and high beta. The low beta rhythm is usually localized in the frontal and

occipital lobes and the other two are less localized. There are more irregular than the alpha rhythm and are associated with psychophysical activity, states of agitation, alertness or mental activity when solving problems.

To record the patient's brain activity or Human-Computer Interaction (HCI) in bands δ, θ, α and β, we use the ThinkGear ASIC Module v1.0 (TGAM1) passive sensor developed by the NeuroSky company (see Fig. 1), measuring the frequency bands of brain waves and generating raw time series, i.e. raw sound signals [28], [29]. These sound signals were recorded from the patient with ISCP by the first frontopolar electrode (F_{P1}) of 10-20 System of Electrode Placement [30].

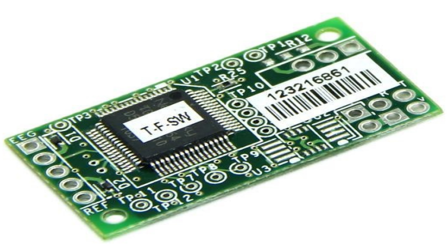

Fig. 1. Signal acquisition tools: Sensor ThinkGear ASIC module v1.0 (TGAM1)

Fig. 2. Signal acquisition tools: Hydrophone 8103 of Brüel & Kjaer

This sensor enables to construct fractal time series to be compared with spectrogram obtained from power analysis of bioacoustic signals, in order to insight relevant information about the dynamics pertaining to the behavior of the patient's brain Before, During and After DAT.

To collect dolphin's bioacoustic signals, a Brüel & Kjaer 8103 Hydrophone and its coupling attachments are used to sound card that allows communication with computer equipment. This small and highly sensitive transducer is used to perform absolute sound measurements in frequency ranging from 0.1 Hz to 180 kHz with a reception sensitivity of -211 dB referred to 1V/μPa. It has high sensitivity relative to its size and good overall characteristics, making it generally applicable for both industrial and educational use. The high-frequency response of Type 8103 is especially valuable when conducting acoustic investigations of marine animals and in measurement of pressure distribution patterns by ultrasound. It is also useful for cavitation measurements. Fig. 2 shows the main external characteristics of the type 8103 hydrophone.

The applied Signal Acquisition Tools are described in detail in [31], while the mathematical tools used in this work are explained in [32].

C. Stimuli

Sonar of dolphins in conjunction with the resonance characteristics of humans are contributing factors to the current interest of this type of alternative therapies by researchers and foundations devoted to the treatment of neurological ailments, mainly in children [15], [16] with developmental disorders .

In [18] is argued that a dolphin orients its sonar by itself to the cranial area of the patient during DAT.

Hence, there is an increment of the Power Spectral Density when dolphin is closer to the patient, and thus a certain resonance frequency is yielded in specific parts of the patient's body (see Table I).

TABLE I. RESONANCE FREQUENCY RANGE OF THE PATIENT'S BODY

Human body parts	Range of Resonance Frequency (Hz)
Arms and shoulders	[2,8]
Chest	[2,12]
Hips	[2,8]
Lower back	[6,12]
Abdomen	[2,14]
Head	[8,27]

Therefore, the main issue is that dolphin's sonar produces resonance of different parts of the human body, yielding effects on the nervous system of the patient via psychological changes [33]. This process is attributed to the generation of endorphin in the brain, bringing about the activation of collagen molecules throughout the body.

Positive effects of DAT have been observed since 1978 in [34], [35], who proposed an experimental model of assisted-therapy to be a starting point for complementing the systematic rehabilitation, highlighting relevant factors in the effectiveness of these alternative therapies such as the type of patient condition, the water temperature, and the time required in a day. Each DAT is different, according to the condition to be treated as well as the patient specific needs [15], [16]. The conclusion of these works is that patient improvement depending only on testimonials explained by parents of the patient to therapists and trainers.

For this reason, some authors in [36] refer to DAT such as a *scientific Heresy* owing there had not a study where the brain activity of patients were measured and explored during DAT from computational and mathematical points of view.

D. Methodology

1) Model: The Healthcare Informatics System developed in this works relies on information technology, allowing to

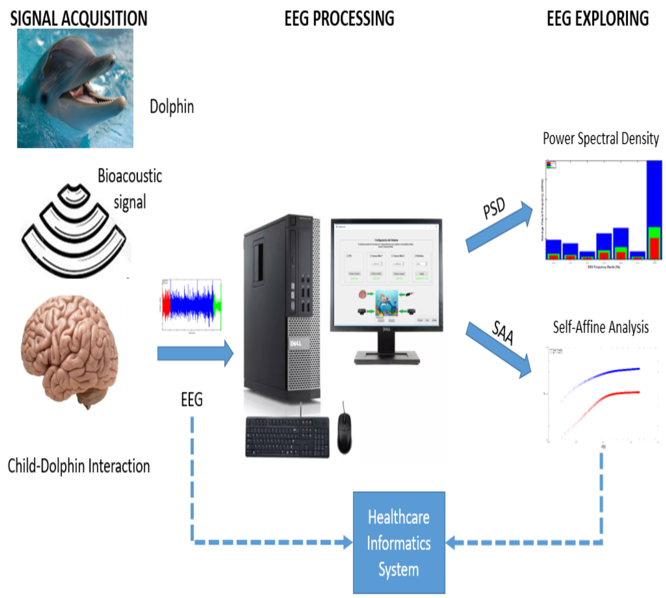

Fig. 3. Four-stage first-order cybernetic model of the healthcare informatics system or HIS-DAT

organize and analyze health (EEG signals) records to measure and evaluate healthcare (effectiveness) outcomes.

Our Healthcare Informatics System is included in a model designed for measuring and assessing the effectiveness of DAT in a patient with ISCP. This model can be summarized in a four-stage first-order cybernetic model (see Fig. 3): i) *Signal Acquisition*, ii) *EEG Processing*, iii) *EEG Exploring* and iv) *Healthcare Informatics System (HIS-DAT)*. The input of this system is the *Signal Acquisition* stage wherein acoustic activity of the dolphin's sonar stimulates the patient's brain activity, considered the Child-Dolphin Interaction. In the *EEG Processing* stage, biosignals acquired in parallel in the previous stage are digitized and transformed into the frequency space. Subsequently, an *EEG Exploring* stage is performed as the output of the system, summarizing the behavior of biosignals by means of both a Power Spectral Density and a Self-Affine Fractal Analysis. Finally, in the fourth stage the Child-Dolphin Interaction is contrasted with non-parametric mathematical methods applied, in order to assess how effective the assisted therapies were for the patient, i.e. HIS-DAT focuses on making sense of the feedback or Input / Output interaction of the entire DAT-system.

2) Procedure: DAT can be carried out both in a tank and in open sea, contributing to the effectiveness of this kind of alternative therapies. There is no a standardized procedure for this type of assisted-therapies, since they vary to adapt to both patient and location conditions. Hence, depending on the sort of facility, DAT are performed differently, but there are prevailing factors [37], [38].

It is noteworthy mentioning that National Polytechnic Institute of Mexico by means of its Ethics Committee in document number D/1477/2020 approved this methodology for sampling and treating not only patients with ISCP but also female bottlenose dolphin.

In Delfiniti-Ixtapa facilities everything starts with an interview to the parents in order to learn more on their children, including the infants' diagnosis and behavior. This is vitally important in children whose communication skills are limited, and helps adjust therapies to the needs of each patient [39], [40].

Already in the water two specialists are present during the process: i) dolphin trainer and ii) therapist. Dolphin trainer supervises the behavior of dolphin while therapist places dolphin in certain parts of the patient body, especially those points that are located on the patient skull. Since a patient is introduced into the water, his/her motor exercises begin to stimulate the movement of the joints and effort in the muscles for carrying out a treatment focused on diseases that attack the central nervous system, regardless of the type of therapies [41], [42], [43]. Moreover, these exercises are performed as a warm-up before DAT and generate trust between patient and therapist, a crucial element during therapies. For patients with motor severity, water provides support in the body enabling them to perform more postures. Besides, water helps exercise muscles and joints, activating blood circulation to induce the desired state of relaxation.

The introduction of dolphin into the procedure is at discretion of the human specialist, taking place until the patient's confidence enables it. In [16] describes how many times in a day dolphin accepted the presence and the interaction of patient, before and after being trained for that purpose. After training dolphin, patient displayed feelings of joy, acceptance and a state-reflective positive [44].

The Delfiniti-Ixtapa personnel have developed their own Intervention Methodology for performing DAT (*IM4pDAT*). Thus, in the interaction with the dolphin, the patient is guided to caress it with complete movements that stimulate orientation and movement in three dimensions: length, height and depth [44]. To perform effectively DAT, the cooperation of both parties is stimulated by rewards, which is known as conditioned behavior (see Fig. 5). If *IM4pDAT* are done correctly, patient is rewarded by caresses, games and activities with dolphin, while dolphin cooperation is rewarded by attention and food as prizes.

Fig. 4 shows a Therapist who indicates to trainer where to orient the dolphin's nose to specific points on the patient's body until a light-touch is performed. Starting with the upper part of the chest where the thymus is located, a gland that develops T lymphocytes and responsible for the cellular immunity of the human body [45]. The dolphin's sonar emission can be perceived by therapist, either by waves in the water or by a sensation in the area where the body is in contact.

Next points to be in touch with dolphin are the frontal lobe located on the patient's forehead, and later in nape of the neck where the medulla oblongata is located, this latter communicates the peripheral nervous system and the spinal cord with the brain. Subsequently, therapist orients dolphin to the middle of head, in order to locate it in pituitary gland, a gland that is part of endocrine system responsible for producing hormones that carry instructions and information among several cell groups. Dolphin is oriented towards occipital and parietal of patient in an upright position, where it is usual that certain discomfort occurs when dolphin is approached to left hemisphere of patient's brain. In [46] it is established left hemisphere is dominant for mathematical comprehension and language. In Delfiniti-Ixtapa a therapies last from 15 to 30 minutes, according the patient's needs [44].

Fig. 4. Dolphin-assisted therapies in mexico: development

Fig. 5. Dolphin-assisted therapies in mexico: dolphin feeding

As mentioned before, DAT are alternative therapies increasingly recommended by foundations to support children with neurological disorders and rehabilitation centers, in addition to being recommended by the Family Integral Development System (DIF, in Spanish) in Mexico [16], [47].

Nonetheless, there are bad practices when DAT are performed, as in all human activity, since it is still a business goal that increases in popularity over the years. Hence, DAT have been seen as a procedure focused mainly on animal rights and without any scientific evidence on its effectiveness. However, in [16], [48], [15] it as also encouraged the emergence of new research to improve techniques to be carried out, in order to assess the effectiveness of this method in the treatment of several disorders, diseases and ailments.

To understand the origin of benefits of DAT and try to offer scientific evidence about its effect in children with ISCP, a Human-Computer Interaction model is developed for the frequency-analysis in sessions lasting 8 minutes, proposing two sub-types of experiments. On the one hand, one session at a pool without a dolphin for 6 minutes measuring patient's brain activity in four exercises:

1) Before therapy in the water (1 min).
2) During therapy in the water without a therapist (2 min).
3) During therapy in the water with the therapist (2 min).
4) After a water therapy (1 min).

On the other hand, one session at the dolphin's tank with salt water, previously informing the completion of DAT and measuring patient's brain activity in five exercises:

1) Before DAT (1 min).
2) During DAT without therapist and without dolphin (2 min).
3) During DAT without therapist and with dolphin (2 min).
4) During DAT with therapist and with dolphin (2 min).
5) After DAT (1 min).

The above mentioned experiments are designed to independently compare the effect in DAT under different factors such as water, wind or dolphins [49]. To verify the expected outcomes for the experimentation, the raw-results were acquired using *IM4pDAT*.

E. Data Acquisition and Analysis

The correlation analysis between bioacoustic signals emitted by dolphin and an EGG signal from patient with ISCP is performed from a software developed in the programming-language MATLAB because of being a programming language oriented to design scripts, i.e. an interpreted language made-up a set of predesigned functions for execution of programs in mathematical language. To perform only the program's final stage, i.e. analysis of collected data, minimum requirements of MATLAB R2016b release are demanded.

Data-acquisition process during DAT requires the following devices:

- Sensor ThinkGear ASIC Module v1.0 (TGAM1).
- 2 Web with Standard or SD Resolution, although it supports high-definition or HD.
- USB-DAQ 8/2-ch production analysis card.
- Charging to Delta Tron converter with integrated TEDS.
- BNC (male) to 10-32 UNF (female) adapter.
- Brüel Miniature hydrophone & Kjær Model 8103 with 10-32 UNF cable (male).

Besides the analysis of biosignals performed in this research, a system programmed in Matlab R2022a is also developed in order to create folders on local disk of computer equipment used for this analysis. These folders store samples collected in each analysis step. Integrated development environments or IDE's are designed for each part of the process to be managed intuitively by users, so that the program execution is divided into modules to provide the user graphical access to system control. Likewise, each module is divided into functions with specific goals for successfully running of the program by dividing the process into sub-sequential processes. Each function is executed by indirect calls, allowing sequential execution of same, as well as transfer of data among them. Fig. 6 and 7 show both IDE Configuration for signal acquisition and the one for storing Basic patient information, respectively.

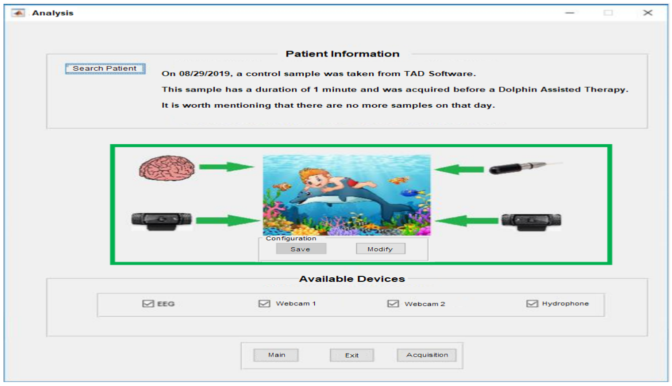

Fig. 6. Data analysis: configuration for signal acquisition

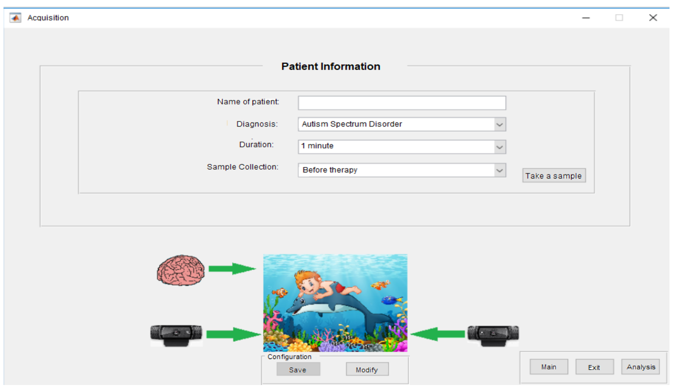

Fig. 7. Data analysis: basic patient information

For the statistical analysis of time series, in this work an Self-Affine (or Fractal) Analysis was performed. A fractal object is scale-invariant or self-affine when it remains invariant under an anisotropic transformation scale (different scales in all directions). Despite their differences, on a transformation scale, directions are not completely independent. If, when zooming in, one of coordinate axes is transformed into a factor b, $x \rightarrow bx$, the rest of coordinate axes must be rescaled into a factor b x_i $\rightarrow$ $b^{ai}x_i$, in order to preserve the invariant set. Exponent ai is called the Hurst exponent (or dynamic scaling exponent) and tell us what the degree of anisotropy or correlation of the set is [50].

Biosignals, specifically EEG signals, representing a fractal system having self-affinity at a macro level and at a micro level. Small changes create a huge variety of patterns at both micro and macro levels. Fractal analysis makes it possible to determine fractional dimension and detect properties of self-affinity in objects or time series subject to investigation and possessing complex characteristics [51], [52].

In this work, we apply Self-Affine Analysis as theoretical basis for evaluating dynamics of EEG signals of patient with ISCP owing this mathematical tool gives us a notion of the behavior of cerebral signals. From EEG time series it is possible to explore the behavior of many biological complex systems at different time-scales. Expected relationship between values of EEG at time t and at time $t + \tau$ is a correlation relationship in brain activity. Otherwise, a stationary time series has correlation when it depends only on time interval between two observations and falls to zero fast enough while increasing, reflecting the fact that influence of past values decreases with considered delay [50], [53], [51], [52].

Thus, evaluation of Hurst exponent is a first step in recognition and characterization of complex dynamics in EEG time series. This analysis makes it possible to distinguish a random behavior from a non-random one.

Likewise, a EEG time series with some level of pre-visibility will show positive self-correlation. Contrarily, a EEG time series with negative self-correlation has no level of pre-visibility. A Hurst exponent ranging $0.5 < H \leq 1$ corresponds to EEG time series showing a period of growth followed by another analog. This means that one increase is more likely to be followed by a similar one; this is known as positive self-correlation [53].

While values located at $0 < H < 0.5$ correspond to a behavior of one period of growth followed by another of decrease, or vice versa, there is more probability that next period is below average; it has a negative correlation. In addition, $H = 0.5$ corresponds to a random movement; an increase can be followed by a decrease or by a similar one. Finally, the movements do not display any memory, it has auto-correlation equal to zero, namely $H = 0$. All this will give us information about the behavior of patient with ISCP when his/her brain is excited or not by a bioacoustic signal emitted by the dolphin [53].

III. Results

This section is divided into three main parts. The first describes how the performance or test operation of biosignal acquisition equipment is validated. The second explains the Power Spectrum Density results. Finally, the third shows the Self-Affine Analysis results.

A. Performance Validation

A data capture was realized using all the sensors for testing the system operation. This test lasted 5 minutes with the dolphin presence to capture the bioacoustic signal by using the 8103 hydrophone. Additionally, a control subject without any diagnosed condition was positioned on the side of the tank to perform the EEG analysis on it.

Once data acquisition process was completed, *Analyzing* IDE option corresponding to *FFT* option was selected in order to verify whether the use of the hydrophone is part of the saved settings. Hence, an indirect call is made to a function to graph the raw-data, both from the hydrophone and from the EEG. Firstly it is set-up the following: i) the hydrophone's sensitivity, ii) the total sample, iii) the analysis time (in this case, 5 minutes), and iv) the folder for the patient as the destination path for the outcomes. Besides the raw-data collected are plotted to yield the time series corresponding to the Volts referred to Pascals (V/Pa) captured by the hydrophone in each $1\ /f_s$ seconds (see Fig. 8). Images generated by webcams are saved as image-files in the patient's folder.

A DAT session was studied from the average frequencies obtained for the histogram of this Experiment, both from the EEG and the hydrophone 8103. These frequencies were estimated in an expected range for a patient in a relaxed state and a dolphin with little activity, respectively.

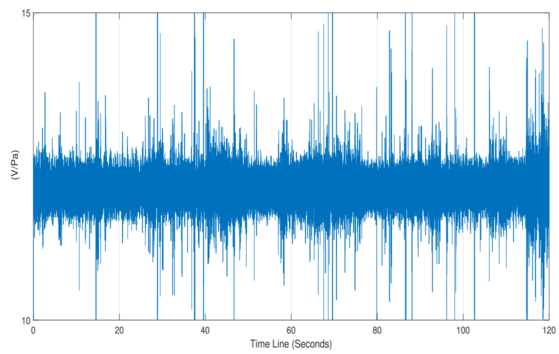

Fig. 8. Time series of the hydrophone resulting from the test

B. Power Spectrum Density

The power density was estimated via an indirect call to a function by adjusting both the minimum frequency to which the hydrophone is sensitive ($f_{min} = 0.1$ Hz) and the sampling frequency ($f_s = 96000$ samples per second). The *pwelch* function is applied inside the MATLAB *Signal Processing Toolbox* to obtain the Welch transform using a kaiser window of size (2/f_{min})xf_s. In Fig. 9 is shown the graph resulting from the estimation of the power density expressed in decibels (dB) and referred to Hertz, for each of the frequencies captured by the hydrophone 8103 during the experimentation.

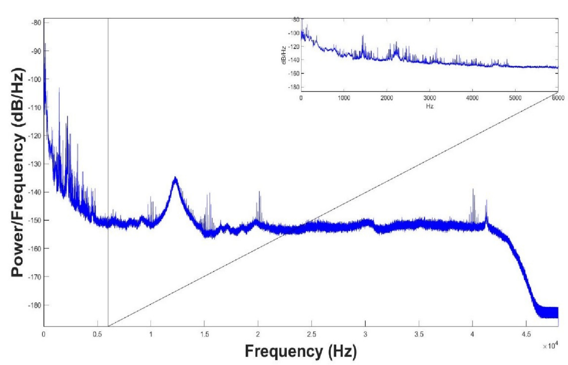

Fig. 9. Periodogram of the hydrophone resulting from the test

Then, the *spectrogram* function is applied inside the MATLAB *Signal Processing Toolbox* with a *kaiser* window of size (2/0.1)xf_s to calculate the Fourier transform in short-time of the frequencies captured every 1 /f_s seconds. This is required to define a normalized-vector to the maximum frequency estimated by the hydrophone. As a result, the spectrogram of Fig. 10 is constructed, depicting a heat-map where each column contains the estimate of the power density of frequencies captured while running the experiment. Fig. 10 and 11 show a spectrogram of biosignals from patient's brain activity and dolphin's echolocation, respectively. These graphs are stored with the patient's name as *image files.jpg* in the selected folder as the *Patient Data*.

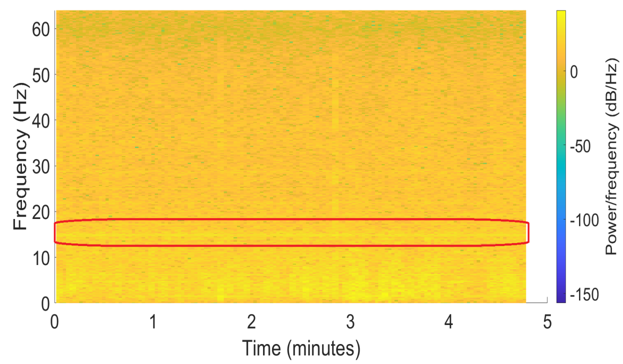

Fig. 10. Spectrogram resulting from the test from EEG

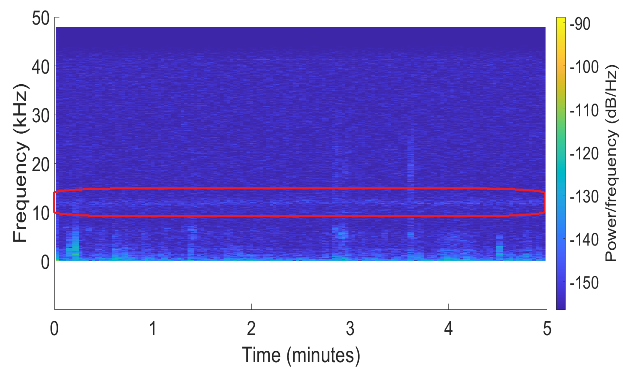

Fig. 11. Spectrogram resulting from the test from hydrophone

Likewise, Fig. 10 and 11 show three-dimensional graphs where not only whole power given by a frequency is observed, but also the moment when a sample manifested certain frequency. Lighter areas point out higher power of a frequency at a certain moment and, on the contrary, dark areas indicate lower power. Thus, after analyzing these two-spectrograms it is found (in red) a clear activation of the brain of patient with ISCP in $\beta = 12$ Hz frequency band, which are related to a state of alert and conscious attention, at the same time when dolphin emits at approximately 12 KHz. This means an indirect activation of the child's brain caused by dolphin's echolocation during DAT.

Fig. 12 shows the resulting histogram from the average of the power of frequencies captured during the experimentation, in intervals of two octaves. Although the hydrophone 8103 is sensitive until 180 KHz, its maximum frequency can be represented as nineteen octaves. For this experimentation only the first-twelve octaves were considered, ranging from 0 to 4096 Hz due to a greater occurrence of the highest powers from seven to ten octaves.

For the data generated from the EEG signals, we also apply the same functions for graphing and analyzing the hydrophone,

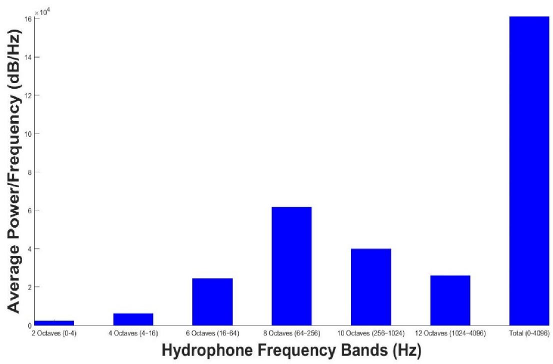

Fig. 12. Histogram of the hydrophone resulting from the test

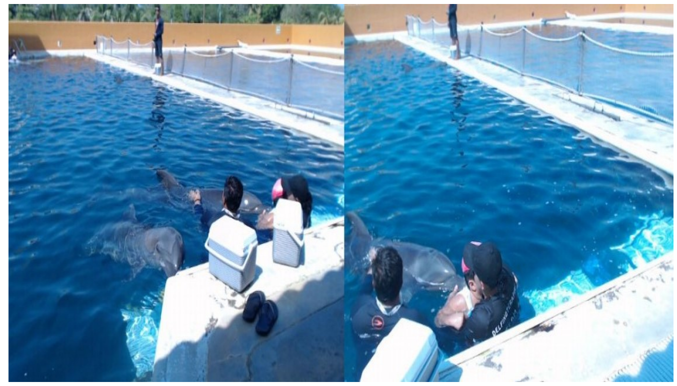

Fig. 14. DAT given to a patient with spastic cerebral palsy in Delfiniti-Ixtapa, Mexico

and performing a similar analysis to the hydrophone without plotting in octaves but plotting in frequency bands of brain activity, such as δ (0.5-4.0 Hz), θ (4.0-8.0 Hz), α (8.0-12.0 Hz), beta β (12.0-30.0 Hz)[54].

Once data processing is finished, a new IDE is opened (see Fig. 13(a)) to choose between viewing the outcomes of the sensor *EEG* (see Fig. 13(b)) or the *Hydrophone* (see Fig. 13(c)). If it is wanted to return to the *Analysis* IDE, it must be pressed the return button. The high-quality versions are located in the same folder selected as the *Patient Data*.

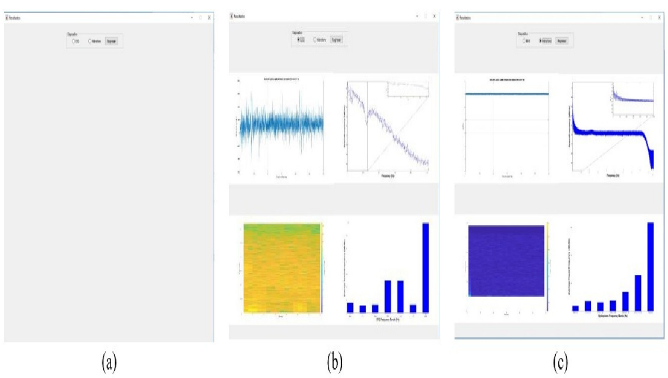

Fig. 13. Results of ISCP patient. (a) window of the Integrated Development Environment (IDE), (b) fast fourier transform for EEG signal, and (c) fast fourier transform for hydrophone biosignal

A frequency analysis during DAT is carried out from the signals captured in this cetacean via the 8103 hydrophone and the EEG signal corresponding to a DAT performed on a patient with ISCP (see Fig. 14 [55]).

In Table II is shown the recorded outcomes corresponding to the average of frequencies obtained from the EEG signals. High-frequencies ($\alpha + \beta$ bands) refer to an attention state and low-frequencies ($\delta + \theta$ bands) correspond to a relaxation state in a human. In the case of water therapy without a dolphin, it is observed a decrease at the end of therapy of 72.77% in the power of the patient's brain activity for low-frequencies and 85.33% for high-frequencies. Contrarily, in the case of DAT was found an increase of 9.73% and 6.85%, respectively, at the end of therapy. In both sub-types of experimentation, the greatest power is recorded when the main factor of change is introduced in each therapy, being the therapist in the case of therapy in the pool and the dolphin in the case of assisted therapy. Thereby, during DAT the greatest power is recorded between both sub-types of experiments. The increase observed is 160.3% in low-frequencies and 143.84% in high-frequencies regarding the frequencies recorded Before DAT.

C. Self-Affine Analysis

Fig. 15 and 16 show the main outcomes for RAW-EEG brain activity. Fig. 15 shows the cerebral activity of patient with ISCP undergo DAT with dolphin and therapist. Fig. 16 presents the results in terms of voltage fluctuations regarding brain activity, estimated by a Self-Affine Analysis. The three-curves depict the voltage fluctuation behavior at different time-scales: i) in red color the sample taken Before DAT, ii) in blue color the sample taken During DAT, and iii) in green color the sample taken After DAT. The resulting values of the Hurst exponent are: i) Before DAT $H = 0.4133$, ii) During DAT $H = 0.3898$, iii) and After DAT $H = 0.4462$; in all cases the behavior of patient's brain activity is antipersistent or displayed negative correlations ($0 < H < 0.5$)., i. e. there is a constant change in the patient's brain activity

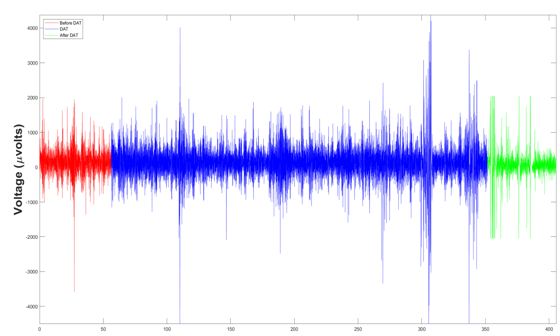

Fig. 15. Main results for RAW EEG brain activity of the child with ISCP: i) in red color Before DAT, ii) in blue color During DAT, and iii) in green color After DAT

TABLE II. RESULTS FROM PATIENT WITH ISCP, EXPERIMENT CARRIED OUT ON JANUARY 25, 2020. THE BOLD BARS INDICATE THE BEST THERAPEUTIC EFFICIENCY IN TERMS OF POWER DENSITY

Therapy	Bands	Before	During	After	$\delta+\theta+\alpha+\beta$ Before	$\delta+\theta+\alpha+\beta$ During	$\delta+\theta+\alpha+\beta$ After
Pool without therapist	$\delta+\theta$	423.65	256.56	115.36	1097.75	563.28	214.28
	$\alpha+\beta$	674.1	306.72	98.92			
Pool with therapist	$\delta+\theta$	423.65	365.08	115.36	1097.75	771.99	214.28
	$\alpha+\beta$	674.1	406.91	98.92			
DAT without dolphin and therapist	$\delta+\theta$	262.48	222.89	288.02	596.98	649.42	645.43
	$\alpha+\beta$	334.5	426.53	357.41			
DAT without dolphin and with therapist	$\delta+\theta$	262.48	217.5	288.02	596.98	477.77	645.43
	$\alpha+\beta$	334.5	260.27	357.41			
DAT with dolphin and therapist	$\delta+\theta$	262.48	**683.26**	288.02	596.98	**1498.9**	645.43
	$\alpha+\beta$	334.5	**815.64**	357.41			

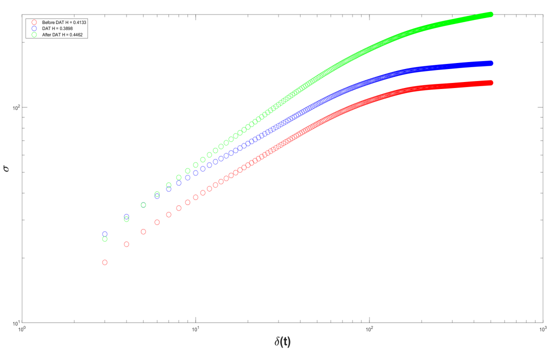

Fig. 16. Results form self-affine analysis describing the voltage fluctuation behavior at different time-scales: i) in red color before DAT, ii) in blue color during DAT, and iii) in green color After DAT

IV. DISCUSSION

From Table II, it can be observed that the greatest power occurs both at low-frequencies ($0.5 - 8.0\ Hz \rightarrow \delta + \theta$) and at high-frequencies ($8.0 - 30\ Hz \rightarrow \alpha + \beta$) when performing DAT with a therapist working on the patient. In addition, when frequencies ranging from 0.5 to 30.0 Hz ($\delta+\theta+\alpha+\beta$), DAT gets the greatest power during therapy. Moreover, a simulated DAT in a pool is working as a relaxant since it has a tendency to reduce the power of brain activity. While tendency of DAT is to enter with a certain power, it increases almost 3-fold the power and produces a greater effect than initial therapy, as well as it keeps high-frequencies responsible for concentration.

In [56] and in [57] have been pointed out that a complete conventional therapy should increase the brain's highest-frequencies in conditions, e.g. Attention Deficit Hyperactivity Disorder since it makes patient's concentration be kept, an effect that does occur in DAT.

Concerning to outcomes resulting from the Self-Affine Analysis, it is observed: i) Before DAT $H = 0.4133$, ii) During DAT $H = 0.3898$, and iii) After DAT $H = 0.4462$. Thus, in the full-session of DAT the patient's brain activity displays only negative correlations at different time-scales, i.e. the patient's brain activity increases and decreases all time long, but the greatest changes occurred During DAT due to it yields the lowest Hurst exponent ($H = 0.3898$), i.e. the most negative correlation displayed.

Finally, it is worth mentioning that it is not possible to compare the results obtained in this article with those yielded by other related articles on the topic owing non-parametric and non-linear mathematical methods such as this work are not used and are only limited in many cases in the opinions of parents or simply basic descriptive statistics such as the mean or standard deviation. Besides, this work contains just a single case study, which gives a first approximation of what happened with the brain activity of a patient with cerebral palsy during DAT, but it is the basis for future research, which should have at least both control and intervention subjects in order to strength our findings.

V. CONCLUSIONS

Family members of patients with Infantile Spastic Cerebral Palsy (ISCP) appeal to both conventional and alternative therapies such as dolphin-assisted therapies (DAT). This work trials to find scientific evidence about the effect of DAT in a child with ISCP for improving his functional abilities and quality of life. Therefore, we develop a four-stage first-order cybernetic model: i) Signal Acquisition, ii) EEG Processing, iii) EEG Exploring and iv) Healthcare Informatics System (HIS-DAT) to measured the brain activity of this patient by collecting and exploring two passive-sensor types of biosignals: i) Electroencephalographic and ii) Sonar echolocation of a female bottle-nose dolphin.

We found that the Power Spectrum of signals from EEG and Hydrophone signals yield similar densities along all DAT and increases 3-fold higher-frequency brain activity when the therapist-dolphin pair interacts with the patient. Increments in higher-frequencies, ranging from 12 to 30 Hz ($\alpha + \beta$), corresponding to concentration activities can help not only in patients with ISCP but also in other disorders such as Attention Deficit Hyperactivity Disorder. These findings are supported by the Self-Affine Analysis outcomes, pointing out the emergence of negative correlations from the patient's brain activity during the whole session of DAT but the greatest changes occurred During DAT. Usage of a single child as a case study shows first results of how this patient's brain activity behaves when this brain has neuronal disability and it is auto-stimulated by dolphin's sonar.

The proposed HIS-DAT model stores and retrieves all applicable information regarding patients undergone DAT. HIS-DAT also allows doctors, therapists, dolphins' trainers, and parents to have quick, easy, and efficient access to changes in patients' brain activity Before, During and After DAT in order to evaluate its effectiveness.

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