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Case Report

Case report: Significant quantitative MRI brain volumetric finding associated with electrical brain injury

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A B S T R A C T

Electrical injury (EI) occurs when current comes in contact with the body, and can result in skin burns, tissue damage, respiratory arrest, and death in some cases. Many EI patients experience neuropsychological deterioration and show symptoms of memory problems, post-traumatic stress disorder (PTSD), sensory disturbances, depression, and other cognitive deficits. In this study, we present the uncommon case of a 43-year-old male with a statistically significant increase in his right lateral ventricle after coming into contact with stray voltage. Upon injury, he sustained retrograde amnesia and first-degree burns on his right underarm and on the dorsal aspect of both forearms; the total surface area affected was 3.3%. One month later, he began experiencing anxiety, depression, memory problems, PTSD, and insomnia, all of which persisted up to at least six years after the electrical injury. The patient's magnetic resonance imaging scans were used to perform quantitative volumetric analysis and identify various regions of interest that were statistically significant against Functional Biomedical Informatics Research Network (FBIRN) controls. We ran a two-sample *t*-test of the patient against FBIRN controls (n = 42, mean age = 34.12 years, SD = 11.02 years, females = 14, males = 28) with gender and age as covariates. Regions of interest were identified ($P < 0.5$) using the contrasts generated in the two-sample *t*-test, and fractional anisotropy values were extracted from the patient and male controls (n = 15, mean = 41.47 years, SD = 8.22 years). We found an increase in the patient's right lateral ventricle 2 standard deviations above the mean value of the controls, consistent with right-sided fractional anisotropy abnormalities found in the statistical comparison.

1. Introduction

Electrical injury (EI) is responsible for approximately 1000 deaths and 3–5% of all burn admissions per year in the US [1]. EI victims are not only hospitalized for burns, but also for skeletal muscle tetany, respiratory muscle paralysis, or ventricular fibrillation [1]. However, these statistics do not include the victims that mainly suffer from the neuropsychological, neurological, and psychiatric sequelae associated with EI.

While the past literature shows that EI sequelae is typically associated with burns due to the current's thermal load and the body's tissue resistance, the literature also shows that remote psychiatric effects are indicative of and distinct to EI [2,3]. White matter abnormalities after EI have also been found on magnetic resonance imaging (MRI) scans [4], particularly hyperintensities in the cerebral corticospinal tract [5–7].

2. Case report

2.1. Case presentation

One morning in the spring of 2009, the 37-year-old patient was walking his dog in a densely populated city, when his dog stepped in a puddle of melted snow and suddenly jumped upwards, yelped, and started convulsing and defecating himself. The patient bent down on his right knee and grabbed the dog with his left arm as he held himself up with his right hand, which was in the puddle. He reported a "buzzing feeling" traveling up his right arm. After bringing his dog to safety, the patient returned to the site, got down on both knees, put both hands in the puddle, felt a "humming" sensation travel up both arms and felt "stuck" in that position for 2–3 s (no-let-go phenomenon).

Immediately after the shock, the patient sustained burn marks and experienced short-term memory loss and fatigue. Three days

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later, the patient saw an internist and reported upper right quadrant pain, headaches, numbness, weakness, fatigue, insomnia, and minimal, first degree burn marks on his right underarm and on the dorsal aspect of both forearms. The surface area was 1.1% for each forearm, and an additional 1.1% for the right underarm, for a total affected area of 3.3%. One week later, the patient received MRIs of the lumbosacral spine, cervical spine and brain which all reported no abnormalities. One month later, the patient visited a psychologist regarding anxiety, insomnia, and depression, and was diagnosed with post-traumatic stress disorder (PTSD) and retrograde amnesia. Three months after the electrical injury, the patient saw an ophthalmologist regarding pain behind his right orbital and "drooping" of the right side of his face; he was diagnosed with Bell's palsy.

Two years after the incident, the patient had an orthopedic evaluation for right side body pain, loss of right hand motor control, right hand tremors, pain behind the right orbital and headaches with no orthopedic abnormalities found. The following day, the patient visited a neurologist and a different ophthalmologist regarding the same symptoms, with no abnormalities found.

Three years after the electrical injury, the patient visited a neurologist regarding hypesthesia in the right side of the face and to pinpricks to the right hand, severe pain in the right arm and hand, moderate pain in the left arm and hand, and was diagnosed with electrocution neuropathy. Five months later, the same neurologist noted improvement of the pain in the right arm and hand area. During the same year, the patient visited a therapist and was diagnosed with PTSD, severe anxiety, and situational depression and was prescribed psychotherapy as treatment.

Six years after the injury, additional documentation of the damage sustained from the electrical injury was needed to provide objective evidence as part of a lawsuit against the electric company responsible for the exposed wires. The patient visited our laboratory for an MRI DTI and quantitative volumetric analysis, and a clinical neuropsychologist for an exam. At the time of the neuropsychological exam, the patient was taking Bupropion XL, Clobex, Hydrocodone/Acetaminophen, melatonin, Klonopin (clonazepam), Namenda (memantine), Neurontin (gabapentin), and medical marijuana. On the Diller-Weinberg Test, the patient missed 39/47 stimuli, and his visual encoding/processing speed on specific Wechsler Adult Intelligence Scale (WAIS-IV) subtests was between the 1st and 5th percentile. On the dominant finger-tapping test, the patient scored in the 5th percentile. His performance on a timed task of fine motor dexterity was impaired between 2 – 3 standard deviations below the mean, and his motor and processing speed index was in the 2nd percentile, which is typical residual of electrical injury. The patient scored 20 less points on his Performance intelligent quotient (PIQ) than his Verbal IQ (VIQ), which is statistically significant and notably unusual. He scored as severely depressed on his Beck, and has had severe chronic pain and PTSD symptoms in the clinical range.

The patient's past medical history was significant for meningitis at age 10, and arthritis and hypertension as an early adolescent. The patient underwent several unrelated orthopedic surgeries from sports related injuries, with the last surgery being sixteen years before the electrical injury. According to his ex-fiancé, the patient was very social and outgoing before the electrical shock, while he became withdrawn and isolated afterwards. The patient enjoyed activities such as surfing, swimming, hiking, basketball, and skateboarding, all of which he was unable to do, or did differently, after the injury.

At the time of the incident, he was in good health and working as a physical trainer.

2.2. Investigations

The patient received an MRI scan in the spring of 2015. The scan was acquired using a 3 T Siemens MRI scanner that captured 160 images using T1-weighted magnetization-prepared rapid gradient echo sequences of the sagittal view, and 93 images using echo planar multidirectional diffusion weighting imaging. The first set of images was uploaded onto CorTech Lab's NeuroQuant software for volumetric analysis (Table 1).

The second set of images were preprocessed using the Functional Magnetic Resonance Imaging of the Brain (FMRIB) software library (FSL) and were then compared against 42 Functional Biomedical Informatics Research Network (FBIRN) controls (n = 42, mean age = 34.12 years, SD = 11.02 years, females = 14, males = 28) using Matlab's Statistical Parameter Mapping (SPM) feature for diffusion tensor imaging (DTI) analysis. After running a two-sample *t*-test with age and gender as covariates, SPM then generated positive and negative contrasts for the patient ($p < 0.01$, voxel = 30), which showed areas of significantly increased or decreased fractional anisotropy (FA) values of the patient. These contrasts were then overlaid with the patient's MRI scans using the Volume Imaging in Neurological Research, Co-Registration and Regions of Interest included (VINCI) image analysis software. VINCI was also used to outline regions of interest (ROIs); the most significant are shown in Fig. 1. Fifteen of the 42 FBIRN controls (mean = 41.47 years, SD = 8.22 years, males) were loaded onto VINCI. The patient's ROIs were then pasted onto the control images. The mean FA values of the patient and the controls were recorded and then, using Microsoft Excel, a P-Score was calculated for each region of interest (ROI).

The patient's and control's structural segmentation images (Fig. 2) of the brain and skull were taken from the NeuroQuant quantitative volumetrics output, while the ROI was segmented out from the 3D volumetric brain image. The skull outline was visualized, volume-rendered, and adjusted for opacity using Advanced Visual Systems (AVS) software. The ROI was visualized as an isosurface map and arbitrarily colored blue to be distinguished from other brain structures.

3. Discussion

3.1. Background/Theory

Most electrical injuries happen in the workplace, while some occur in household settings [8]. In dense cities that experience heavy snow during the winter, like Boston or New York City, residents are at a higher risk of electrocution through stray voltage when the snow starts to melt [9–11]. Stray voltage is the unintended occurrence of an electrical potential between two objects due to a fault in an electrical system (e.g. a live wire or a poorly insulated power system) and is defined to be less than 10 volts by the U.S. Department of Agriculture [12]. These circumstances, coupled with the increased conductance caused by high-salinity snowmelt, can charge normally non-threatening metal objects, or puddles with ample amounts of stray voltage.

Electrical injury occurs when a person has at least two points of contact with two sources of different voltage, one of which may be the earth ground [13]. The extent of electrical injury is dependent on the voltage, amperage, path of and type of the current (alternating current (AC)/direct current (DC)), duration of contact, and premorbid state of the patient [14]. The current passing through an object with resistance in an external electric field can be calculated using the following equation:

$$V = IR \quad (1)$$

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Table 1
Patient's quantitative volumetric MRI measurement of his T1-weighted sagittal MRI scan using Cortech Lab's NeuroQuant software.

Absolute volumes (cm^3)	Average	SD	Patient	Z-scores
Left Forebrain Parenchyma	573.79	57.17	507.04	−1.17
Right Forebrain Parenchyma	581.10	59.03	514.78	−1.12
Left-Right Forebrain Parenchyma	−7.30	7.35	−7.74	−0.06
Left Cortical Gray Matter	276.44	38.36	260.59	−0.41
Right Cortical Gray Matter	280.67	38.45	266.28	−0.37
Left-Right Cortical Gray Matter	−4.22	5.65	−5.69	−0.26
Left Lateral Ventricle	9.26	3.52	13.66	1.25
Right Lateral Ventricle	8.73	3.49	15.75	2.01
Left-Right Lateral Ventricle	0.53	2.28	−2.09	−1.15
Left Inferior Lateral Ventricle	0.98	0.26	1.08	0.38
Right Inferior Lateral Ventricle	0.93	0.32	0.86	−0.21
Left-Right Inferior Lateral Ventricle	0.05	0.35	0.22	0.47
Left Hippocampus	4.09	0.41	4.48	0.94
Right Hippocampus	4.20	0.53	4.82	1.19
Left-Right Hippocampus	−0.11	0.43	−0.34	−0.54
Left Amygdala	1.91	0.26	2.11	0.78
Right Amygdala	1.91	0.28	1.84	−0.24
Left-Right Amygdala	0.00	0.13	0.27	2.04
Left Caudate	3.60	0.65	3.56	−0.06
Right Caudate	3.78	0.72	3.66	−0.17
Left-Right Caudate	−0.19	0.50	−0.10	0.18
Left Putamen	5.75	0.63	5.52	−0.36
Right Putamen	5.35	0.56	4.96	−0.70
Left-Right Putamen	0.40	0.36	0.56	0.45
Left Pallidum	1.06	0.17	1.05	−0.08
Right Pallidum	1.13	0.19	1.24	0.60
Left-Right Pallidum	−0.06	0.14	−0.19	−0.92
Left Thalamus	8.62	1.00	7.74	−0.88
Right Thalamus	9.90	1.71	8.82	−0.63
Left-Right Thalamus	−1.28	1.17	−1.08	0.17
Left Cerebellum	75.50	8.18	74.74	−0.09
Right Cerebellum	74.55	8.03	70.69	−0.48
Left-Right Cerebellum	0.95	2.47	4.05	1.25

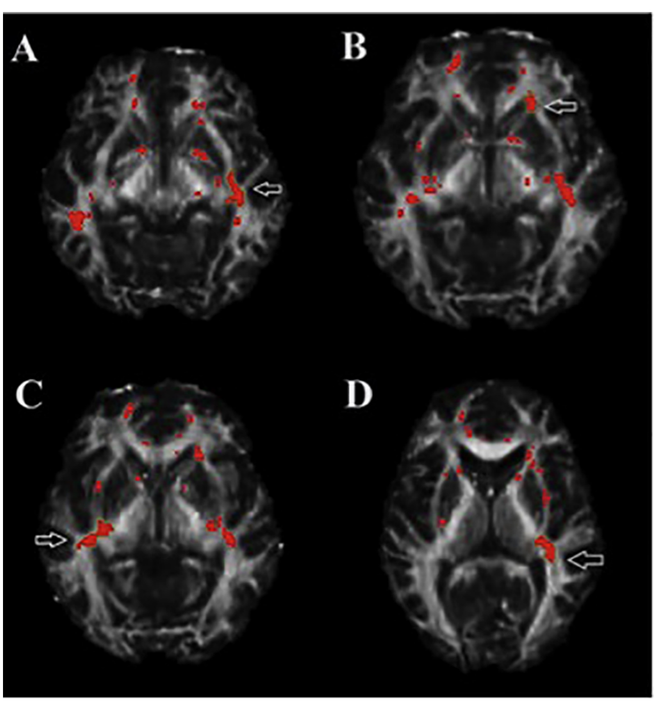

Fig. 1. Positive ROIs (high FA values) captured on VINCI image analysis software; positive contrasts generated using Matlab's SPM feature. Location of ROIs determined using SPM and Talairach Client. A) Right cerebrum, limbic lobe, parahippocampal gyrus ($p = 5.6 \times 10^{-7}$). B) Right cerebrum, sub-lobar, extra-nuclear ($p = 4.6 \times 10^{-5}$). C) Left cerebrum, sub-lobar, extra-nuclear ($p = 3.1 \times 10^{-12}$). D) Right cerebrum, sub-lobar, extra-nuclear ($p = 8.4 \times 10^{-7}$).

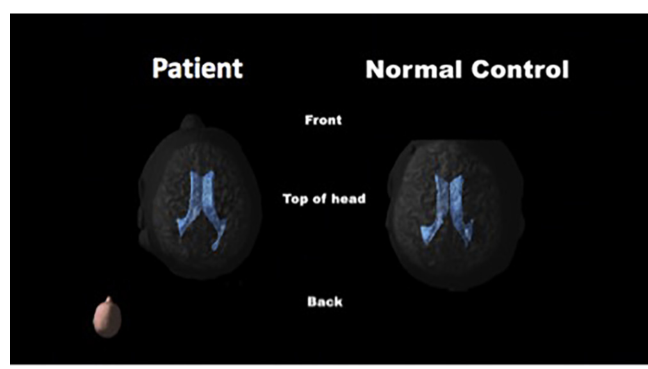

Fig. 2. Patient's and control's image segmentation of brain and skull taken from FreeSurfer and visualized using Advanced Visual Systems (AVS).

where V stands for voltage, measured in volts (V), I stands for current measured in amps (A), and R stands for resistance measured in ohms (Ω).

Skin is the body's primary defense against external electric currents. A dry hand may have a resistance of approximately 100,000 Ω, while the internal body may have a resistance of approximately 300 Ω due to wet and salty tissues under the skin. [13]. Skin resistance can be greatly reduced to approximately 1000 Ω if there is significant physical damage such as a cut, burn or abrasion, or if the skin has been wet [15]. At roughly 16 mA for a 60 Hz AC, the average man would experience a muscle spasm known better as the "no-let-go" phenomenon, in which he would not be able to let go of the current source [13].

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In the presence of an external electric field, cell membrane permeabilization occurs as the lipids in the lipid bilayer undergo reorganization in a process known as electroporation [14]. In turn, cell contents such as ions are able to move freely in and out of cells. Through the phenomenon of electroporation, current is able to travel through and leave the body through the second contact point to a grounding source. Clearly these aspects of EI are quite mechanistic, however, one of its enigmas include the remote neuropsychological deterioration of the patient regardless of the trajectory of the current (whether the current passed through the head or not).

EI has been known to cause a spectrum of neuropsychological and psychiatric disorders. Duff [8] compiled a review of twenty-eight studies of EI and lightning injury patients, logging 2738 victims reporting a total of 4441 signs or symptoms. These signs/symptoms were "categorized into nine different domains of sequelae, which included (1) disturbance of consciousness, (2) attention/concentration deficits, (3) speech/language deficits, (4) sensory deficits, (5) memory deficits, (6) other cognitive deficits, (7) psychiatric complaints, (8) somatic complaints, and (9) neurological complaints". Another study of the long-term sequelae of low-voltage electrical injury done by Singerman [16] reported numbness, weakness, and memory problems as the most frequent neurological problems and anxiety, nightmares, insomnia, and flashbacks of the event as the most frequent psychological problems.

Since the literature suggests EI causes neuropsychological sequelae, it is worth using MRI imaging techniques to examine any structural abnormalities and cerebral lesions [2,8,16,17]. Irregularities observed on MRI scans are generally unique to each EI case, however white matter hyperintensities (WMH) found on fluid-attenuated inversion recovery (FLAIR) image sequences are a common factor [4–7]. The latter three of the case studies cited all report WMH specifically in the cerebral corticospinal tract. EI has also been known to cause hypoxia, which is characterized by cytotoxic edema in the cortex of the central region and the basal ganglia [4].

3.2. Voltage and current approximation

The average lamppost in a densely populated city, such as New York City, works on a single-phase 120 V/240 V 60 Hz, AC received from a nearby three-phase generator [18,19]. The patient received an electrical shock after submerging his hands in a puddle on a sidewalk charged with stray voltage from a nearby lamppost. Workers from the electrical company in the area testified that exposed ends of an electrical cable of a lamppost were causing 8 V of stray voltage. Using the information we know about wet skin resistance, we can also assume that the patient's hand had a resistance of 1000 Ω, while the patient's internal body had a resistance of 300 Ω [13]. Rearranging Eq. (1), we calculate the current passing through the patient's hand to be approximately 8 mA, while the current passing through the internal body is approximately 26 mA. However since salt water is more conductive than pure water, this would have potentially lowered the resistivity of the patient's hand, causing the current passing through his hands to be comparatively higher and thus accounting for the no-let-go phenomenon he experienced [20].

To examine the validity of this approximation, we consider the patient's dog that went into seizure upon stepping in the charged puddle. A study done by Woodbury [21] investigated the stimulus parameters needed to induce electroshock seizures on rats, and found that at 60 Hz AC, the current needed to promote seizures was 17.7 mA. This is extremely similar to the current needed, 16 mA, to induce the no-let-go phenomenon in the average male [13]. Thus we can assume with substantial confidence that the current passing through the patient's hand was roughly around 16 mA AC.

3.3. Review of meningitis history

At age 10, the patient was treated for meningitis. One week after the electrical injury, the 37-year-old patient received a brain MRI that reported no abnormalities. Six years after the injury, the patient had another brain MRI, which was sent to our laboratory. Since the cavitation of his right lateral ventricle is prominent on T1 multiplanar reconstruction (MPR) and T2 FLAIR MRI sequences (Fig. 3), it is highly probable that this particular abnormality was not derived from the patient's childhood meningitis, otherwise it would have been observed by his former radiologist.

MRI DTI analysis done on adult meningitis reports increased FA values in cortical regions, while analysis done on neonatal meningitis reports increased FA values in leptomeningeal regions and decreased FA values in periventricular white matter regions [22–24]. However, to date, there are no studies that report white matter abnormalities found in adults with childhood meningitis, or studies that have assessed high diffusion anisotropy sequelae in patients with a history of meningitis.

3.4. Review of multiple medication effects on neuropsychological testing

At the time of the neuropsychological exam, the patient was taking multiple medications that could have potentially affected cognitive performance. An investigation of these potential effects was conducted.

Depressed patients treated with Bupropion scored similarly to normal, healthy controls on neuropsychiatric tests that assessed verbal memory, visual memory, finger tapping, and symbol digital coding [25]. On the dominant finger-tapping test, our patient scored in 5th percentile, while on the coding subtest, he scored in the 10th percentile. The patient's visual and verbal memory scores were average. In a study that assessed the neuropsychiatric effects of Hydrocodone, subjects that had taken hydrocodone performed 10% worse than the mean on the motor performance test, while no variance was found on simple and complex reaction time tests [26]. Our patient scored in the 2nd percentile on the motor and processing speed index. In a study done on 38 patients taking Clonazepam, 8 patients experienced behavioral side effects (verbal and physical outbursts of anger, argumentative behavior) while 30 patients did not [27]. The mean absolute discrepancy between VIQ and PIQ of the 8 patients was 17.5 points, while the discrepancy between VIQ and PIQ of the 30 patients who did not experience behavioral side effects was 6.5 points. Our patient's VIQ and PIQ

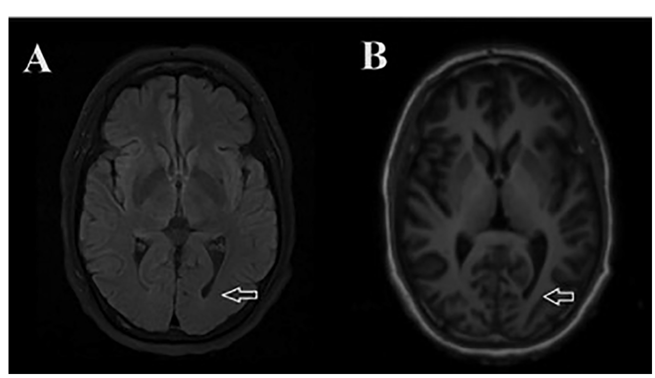

Fig. 3. Out-pouching of right lateral ventricle as seen on A) T2 FLAIR and B) T1 MPR image sequences.

difference was 20 points. No study has been done on the effects of memantine on cognitive behavior for patients without Alzheimer's disease (AD), but for patients with AD, memantine improved language and memory scores in comparison to a placebo group [28]. Gonzalez [29] measured the effects of cannabis on cognitive performance by determining overall indexes of neuropsychological performance and running individual neuropsychological tests (reaction time, attention, verbal language, abstraction/executive, perceptual motor, motor, learning/forgetting). Habitual cannabis users performed 1/5th a standard deviation worse than controls in overall index scores, and had performed significantly worse on memory tests. The patient's performance on memory tests and his full scale IQ were rated average.

No effects of melatonin on neurocognitive performance were found [30]. No effects of gabapentin on neurocognitive performance were found [31].

3.5. Differential diagnosis

Excluding electrical brain injury, the differential diagnosis for DTI and MRI quantitative volumetric abnormalities includes the consideration of Alzheimer's disease, Parkinson's disorder, epilepsy, stroke, tumor, radiation treatment, and psychiatric illnesses such as schizophrenia or unipolar depression. Review of the patient's clinical history and review of the patterns associated with the differential diagnosis rule out the other items on the differential diagnosis such as Alzheimer's disease, Parkinson's disease, stroke, and tumor. The neuropsychological sequelae he experienced (e.g. memory problems, depression, slower cognition, PTSD symptoms) are consistent with an electrical brain injury [2,8,16].

3.6. Quantitative MRI volumetric abnormalities and clinical significance

The patient shows significant increase in the right lateral ventricle volume on quantitative volumetric analysis, which can also be seen in his T1 MPR and T2 FLAIR MRI image sequences (Fig. 3). This right-sided volumetric increase would also be consistent with the 20-point discrepancy of the VIQ and the PIQ since the right side of the brain is more closely associated with the PIQ and the left side of the brain is more closely associated with VIQ [32]. The increased right-sided lateral ventricle would also be consistent with the more prominent right-sided ROIs found on MRI DTI analysis such as right-sided posterior internal capsule, external capsule and arcuate abnormalities. Right-sided abnormalities in areas such as the posterior internal capsule, shown in Fig. 1, would also be compatible with the chronic neuropathy in his left arm since the right side of the brain regulates the left side of the body. Reisner [33] noted that delayed myelopathy (white matter damage) after electrical injury has been established in the literature, and that possible mechanisms include glutamatergic hyperstimulation leading to oxidative stress.

4. Conclusion

After an electrical injury, the patient experienced a long period of psychological deterioration characterized by depression, slower cognition, occupational difficulties, and a significant decrease in performance IQ. The patient's DTI and MRI quantitative volumetric analysis shows an enlarged right lateral ventricle, which is consistent with his decrease in performance IQ. Although it is possible that the patient had already had an abnormal sized right lateral ventricle before the EI, taking into account his former MRI radiologist's report lacking abnormalities, the neuropsychological sequelae accompanied by the EI, and the statistical probability that a normal, healthy person was born with a right lateral ventricle two standard deviations above the average, it is rational to suggest a possible correspondence between the patient's EI and DTI quantitative volumetric results.

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