Targeted shortwave diathermy with perceptual training for severe traumatic optic neuropathy patients

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Research Article

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Abstract

Purpose Patients with severe traumatic optic neuropathy (TON) have limited improvement in visual function despite therapy. The objective of this study was to investigate whether targeted shortwave diathermy combined with perceptual training may enhance visual function in patients with severe TON after endoscopic optic nerve decompression (EOND) surgery.

Methods Eighteen severe TON patients after EOND surgery were included and received targeted shortwave diathermy (SWD) therapy and perceptual training. Visual function, visual evoked potential (VEP), and diffusion tensor imaging were evaluated.

Results Patients with severe TON obtained significant improvements in best-corrected visual acuity and color vision scores at 10 and 16 weeks after rehabilitation ($P < 0.05$). Pearson correlation showed that the age of the subject was positively associated with the visual functions. And the visual acuities of two children were completely lost before and after surgery and visual acuity was regained at the light perception level approximately 2 months after rehabilitation. Additionally, the mean P100 amplitude and diffusion tensor imaging values of affected nerves were changed after 10 weeks of rehabilitation. Pearson correlation showed that the VEP and diffusion tensor imaging parameters were significantly correlated with the visual functions after rehabilitation.

Conclusions Targeted SWD combined with perceptual training exhibited beneficial effects on severe TON patients after EOND surgery. Additionally, the current study reported the first evidence of visual function recovery 74 days after complete visual loss in child with TON when combined rehabilitation was performed.

The trial registry name: Targeted shortwave diathermy with perceptual training for severe traumatic optic neuropathy patients.

URL: ClinicalTrials.gov PRS: Record Summary NCT05140486.

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Key Messages

- Previous studies suggest that the visual recovery may be impossible when VEP results were not recordable within 7 days after injury or after optic nerve decompression surgery.
- The presented study indicated that visual function recovery occurred 74 days after complete visual loss in child with traumatic optic neuropathy when combined rehabilitation was performed.
- The VEP and diffusion tensor imaging parameters, which were significantly correlated with the visual functions, might be the predictors of potential visual function recovery.

Introduction

Traumatic optic neuropathy (TON) results from an impact injury to the optic nerve and causes acute axonal impairment with a partial or complete vision loss [1]. Treatment strategies, including corticosteroid administration, surgical optic nerve decompression, or combinations, have been commonly used [1]. However, these treatment effects fluctuated with a wide range because of the relevant prognostic factors, such as surgical timing, the severity of the impairment of the optic nerve and visual loss, and postoperative rehabilitation [1 2]. Recently, various therapeutic modality treatments, including transcorneal electrical stimulation [3] and alternating current stimulation [4], have been applied in patients with TON. However, the results of the treatments have limited benefits in terms of improvement of visual function [5], especially in those patients with severe visual loss.

To maximize the potential of visual functions in patients with TON, perceptual rehabilitation learning was used. A case study reported that this strategy has a beneficial effect on patients with TON, and a larger case-controlled study on the effect of perceptual learning in TON was recommended to substantiate the beneficial effect [6]. Additionally, even though more attention related to the therapeutic techniques for TON has been paid, no diathermy techniques that increase local blood flow have been applied to the management of TON. One of the most important reasons might be the location of the TON is deeper under the skin. The shortwave diathermy (SWD) device is one of the most preferred deep-heating modalities and can heat tissues to 5 cm deep under the skin [7]. This modality is often used to increase arterial blood flow [8] , decrease pain, change physical properties of fibrous tissues, and facilitate the recovery of neurological functions [9]. Because the location of the optic nerve is deeper under the skin, to obtain better physiological effects, the precise location of the impaired nerve is crucial to find a direct and short route to the impaired nerve. In this study, high-resolution computed tomography was used to locate the impaired nerve. Then, targeted SWD therapy based on high-resolution computed tomography location and perceptual training was applied to treat patients with TON after endoscopic optic nerve decompression surgery.

Materials And Methods

Study sample description

A retrospective review has been launched to 18 medical records of consecutive patients with TON in the Department of Otolaryngology–Head and Neck Surgery, Xiangya Hospital, from January 2017 to July 2021. Indirect TON was diagnosed by a history of blunt head or facial trauma combined with decreased visual acuity, color vision, and a relative afferent pupillary defect with a normal fundus during the early period of post-trauma [10]. We excluded cases with direct trauma to optic nerve identified by high-resolution CT scan of the orbital and optic canal. The patients with indirect TON were intravenously administered methylprednisolone (30 mg/kg per day) every day for three consecutive days as previous studies described [11]. Since there was no consensus on grading criteria in evaluating the severity of indirect TON, TON with best-corrected visual acuity equal to or more than 1.85 logMAR after EOND surgery was considered as severe TON, and those patients were recruited in this study. All of the subjects received SWD therapy and perceptual training after EOND surgery.

Interventions

Shortwave diathermy therapy

DL-C Ⅱ (Dajia®, Shantou, China) SWD device was applied in this study, and therapeutic apparatus was delivered at a frequency of approximately 27.12 ± 0.6% MHz in continuous modes with a power of 50 W ± 20%. In our study, two sets of circular capacitive electrodes were used with a diameter of 80 mm for adults and 50 mm for children. The fracture areas were located using high-resolution computed tomography (Fig. 1). One electrode was applied in the temporal area of the ipsilateral side of the injured nerve identified by a three-dimensional alignment procedure through high-resolution computed tomography scan. This area was not only a shorter distance from the skin to the injured nerve but was also as far away from the crystalline lens as possible. To decrease the negative effects of SWD on the nerve systems [12], another circular electrode of SWD was applied in the frontal area of the ipsilateral side of the injured nerve (Fig. 2). In the acute stage of the TON (within 10 days after injury), the athermal mode of the SWD was applied to the marked areas for a 10-minute daily session. Ten days after injury, the microthermal mode was used for a 15-minute daily session. All subjects in the rehabilitation group received SWD therapy 5 days per week for 4 weeks.

Perceptual training

Perceptive learning sessions were composed of a series of training procedures. First, sensory stimulations including touch, stroking, tapping, and pressing on the local area of the ipsilateral eye as well as the surface location of the injured optic nerve were offered. Second, light stimulation was applied at different intensities of bright based on evaluation of the pupillary light reflex of the subject, and avoiding glare and longtime light stimulation on the eye when training (Fig. 3. A). Additionally, the subjects were instructed to enter the bright room from the dark room when they were wearing an eye patch in the intact eye. Third, differentiation of the shapes and objects was performed in dynamic or static states with different colors, different sizes, and different shapes [13] (Fig. 3. B-C). Fourth, different written words with different sizes and different distances were discriminated in the different directions of the eye (Fig. 3. D). Fifth, color vision was trained using real objects or pictures (Fig. 3. E). Finally, the visual field training was scattered in the above training methods. Each training media including the light, objects, words, and color was input from the anterior, superior, inferior, nasal, and temporal sides of the eye. In addition, many training techniques were used in this study. First, visual imagery (VI) training was used when the patients had a complete or severe visual loss. The intervention of the VI training was as follows: the subjects used the intact eye to observe the object for 5 seconds, then they closed their eyes and imagined viewing the object using the injured eye for 10 seconds for 10 repetitions. Additionally, proprioceptive training, including going over the barriers, going up and downstairs, walking the slope, and training the balance, was executed. Finally, constraint-induced perceptive therapy was performed when the visual lesion partially recovered. The subjects wore an eye patch on the intact eye for 30 minutes in one section, 2 to 4 hours a day, 7 days per week (Fig. 3. F). All the subjects received perceptive learning therapy 5 days per week for 10 weeks except constraint-induced perceptive therapy.

Outcome evaluation

All subjects underwent a thorough evaluation of visual function by an ophthalmologist preoperatively, postoperatively, and post-treatment. The ophthalmologic examinations consisted of visual acuity with optimal correction lenses for both eyes, color vision, pupillary light reflex, relative afferent pupillary defects, visual field examinations, visual evoked potential (VEP), and fundoscopy.

Best-corrected visual acuity was measured by a standardized Snellen visual chart. Visual results were converted into logMAR units for the convenience of statistical analysis. Hand motion, light perception, and no light perception were converted to 2.3, 2.5, and 3 logMAR units, respectively [14]. Color vision was evaluated using the Ishihara color vision test 24 plate [15]. The exclusion criterion of the color vision test was congenital color vision deficiency. The number of correct answers in a set of 24 plates was recorded as the color vision score. Relative afferent pupillary defects was evaluated by using a swinging flashlight with a grade of one to five. Pattern visual evoked potential testing was recorded using an MEB-9404C (Nihon Kohden Corp, Tokyo, Japan). The latency and amplitude of the P100 wave in the VEP testing were collected for analysis.

Additionally, a 32-channel head coil on a 3.0T MRI system (Philips, Ltd, Best, the Netherlands) was used for the acquisition of imaging data. T1- and T2-weighted, fat-suppressed images were obtained axially through the orbit and some parts of the brain, including the intracranial portion of the optic nerve, postoperatively and 10 weeks after rehabilitation. Optic nerve diffusion tensor imaging images were obtained using single-shot echoplanar imaging sequences. The images were acquired from the optic papilla to the orbital apex of the optic nerve with 40 contiguous slices. The following imaging parameters were used: acquisition matrix = 80 · 78, reconstructed to matrix = 128 · 128 matrix, field of view = 200 ·200 mm^2, TR = 2214 milliseconds, TE = 82 milliseconds, parallel imaging reduction factor (SENSE factor) = 2, EPI factor = 39 and b = 800 s/mm^2, NEX = 2, slice gap = 0, and a slice thickness of 3 mm. The region of interest (ROI) was manually placed over the optic nerve at the anterior, middle, and posterior segments on the non–diffusion-weighted (b0) image. The fraction anisotropy, mean diffusivity, axial diffusivity, and radial diffusivity of optic nerves were measured.

Statistical analysis

All analyses were performed using SPSS version 22.0 software (SPSS, Chicago, Illinois, USA). After the data passed normality tests and homogeneity of variance tests, the mean, standard deviation (SD), and range values were calculated. We conducted the One-way analysis of variance (ANOVA) to compare the difference before and after treatment intervention for visual acuity and color vision, and the Student's t-test for VEP and diffusion tensor imaging parameters.

Pearson correlation was used to analyze the relationships between age, visual functions, diffusion tensor imaging, and VEP variables. A P-value <0.05 was considered statistically significant.

Results

Clinical characteristics of the subjects were shown in Table 1. Eighteen patients with unilateral traumatic optic neuropathy were included, 16 of them were males, and 2 of them were females. The average study participant was 25 (SD=17.9) years old. CT scan showed that the patients suffered from orbit, optic canal, or/and orbital apex fractures, and only one subject had no fracture (Fig. 1).

The data of visual acuity and color vision, and VEP parameters are shown in Table 1 and Table 2. After EOND surgery, the visual acuity of the subjects tended to be improved from a mean of 3.00 logMAR to 2.69 logMAR, although this did not reach statistical significance (P = 0.079). Pre-rehabilitation visual acuity significantly improved 10 weeks after rehabilitation (P < 0.01) and 16 weeks after rehabilitation (P < 0.01). Additionally, the visual acuities of two children (Case 3 and case 5) were completely lost before and after surgery and regained visual acuity at the light perception level approximately 2 months after rehabilitation (Additional file 1), reaching 1.0 logMAR (Case 3) and 0.7 logMAR (Case 5) at 16 weeks after rehabilitation. The color vision of the subjects was not significantly different before and after EOND surgery (P >0.05). Pre-rehabilitation color vision improvement was observed 10 weeks after rehabilitation (P < 0.01) and 16 weeks after rehabilitation (P < 0.01).

For the P100 latency of the VEP, no P100 waveform was observed in 14 subjects (77.78%) after EOND surgery, and the value of these P100 latencies was recorded as zero, subsequently resulting in a shortening of the mean P100 latency in all subjects after surgery. Significant differences in the P100 amplitude of the VEP were found 10 weeks after rehabilitation (P < 0.01) (Table 2, Fig. 4). Concerning the parameters of diffusion tensor imaging, the mean fraction anisotropy value in the anterior segment of the affected nerve was significantly higher 10 weeks after rehabilitation (P < 0.05). The mean diffusivity and axial diffusivity values in the anterior and middle segments of the affected nerves were significantly lower 10 weeks after rehabilitation. Similarly, the radial diffusivity value in the anterior segment of the affected nerve was significantly lower 10 weeks after rehabilitation (P < 0.05) (Table 3, Fig. 5). The MRI images indicated that the injured optic nerve showed edema, hyperplasia, displaced and distorted appearance, and axonal degeneration (Fig. 6).

Pearson correlation showed that the age of the subject was positively associated with logMAR of the visual acuity scores 10 weeks (r = 0.48, P<0.05) and 16 weeks (r = 0.738, P<0.01) after rehabilitation. Additionally, the age of the subject was negatively associated with color vision scores 10 weeks (r = -0.61, P<0.01) and 16 weeks (r = -0.740, P<0.01) after rehabilitation. Also, the age of the subject was negatively associated with the P100 amplitude of the VEP (r = -0.545, P<0.05) 10 weeks after rehabilitation. These results might indicate that the age of the patients was significantly correlated with the visual functions. The pre-rehabilitation fraction anisotropy value of diffusion tensor imaging in the middle segment of injured optic nerve was negatively associated with logMAR of the visual acuity scores 10 weeks after rehabilitation (r =-0.529, P < 0.05). Similarly, the pre-rehabilitation fraction anisotropy values of diffusion tensor imaging in the anterior and middle segments of injured optic nerve were positively associated with color vision scores 10 weeks after rehabilitation (anterior r = 0.542, P< 0.05; middle r = 0.577, P < 0.05). These findings indicated that the higher pre-rehabilitation fraction anisotropy value of the affected nerves might have a better prognosis in visual functions after rehabilitation among TON patients. None of the participants reported cataracts, glaucoma, or other adverse effects.

Discussion

To the best of our knowledge, the present study is the first one to investigate the efficacy of SWD therapy in the treatment of TON after EOND surgery. Although the vascular supply dysfunction of the injured optic nerve was one of the main pathological changes after TON [16], and surgical optic nerve decompression partially removes the optic canal to release the compartment syndrome, the vascular supply was not fully rebuilt after surgery. However, no physiotherapeutic modalities are aimed at improving the blood supply of the nerve. Therefore, the SWD device was selected for treating the TON as SWD was one of the most preferred deep-heating modalities [7]. The results demonstrated that patients with TON treated with SWD therapy and perceptual learning had better visual function recovery. These findings might be explained by several contributory reasons. First, the injured areas were located, and electrode areas of the skin were targeted by analyzing the CT scan images using a three-dimensional alignment procedure in the present study. The depth between the electrode of the SWD and the injured nerve was calculated and ensured to be approximately 5 cm. Under this depth, SWD can focus on producing physiological heating by electromagnetic waves [17], increasing local blood flow [7 18] by dilating local arterioles and capillaries [19], subsequently improving ischemia of the injured optic nerve. Second, shortwave radiation was thought to result in attenuation of the activation of inflammatory mediators [20]. Third, SWD has a significant beneficial effect on the recovery of locomotor function, facilitating neuromuscular activity, and has a neuroprotective effect on neurological diseases [21].

To avoid SWD radiation damage to the crystalline lens and the ciliary body, the fracture areas and injured optic nerve were located by CT and MRI scans. Circular electrodes of SWD were applied in the lateral plane more directly to the injured nerve and far away from the crystalline lens as much as possible. The application of SWD to the nerve in the lateral plane will avoid overheating on the crystalline lens [22]. Besides, the application of SWD in nonthermal and microthermal modes for relatively short periods (4 weeks) may protect lens epithelial cells against apoptosis [23]. Therefore, the application of SWD to the optic nerve within a few weeks provides the possibility to exert maximal physiological effects on the nerve without causing possible serious consequences such as cataracts [23]. No cataracts, glaucoma, or other adverse effects of the eyes were observed in this study, and this might indicate the appropriate usage of SWD for patients with TON.

Perceptual learning has been demonstrated to increase visual function in a variety of ocular disorders [13 24], but only one case study indicated that perceptual learning using Gabor gratings with varying contrast had a beneficial effect on traumatic optic neuropathy [6]. Dosher and colleagues indicated that the tasks of perceptual learning were involved in compound stimuli such as textures, depth, motion, objects, and natural scenes [13]. Therefore, the tasks of the perceptual learning tailored in our study are more compound and different from the previous study [6]. In our study, the visual training on light, written words, objects, color vision, visual field, and environment were arranged other than the Gabor gratings. Additionally, local sensory stimulations that can enhance the perception of visual modality at the sensory processing were used [25]. Finally, training strategies such as VI training, proprioceptive training, and constraint-induced perceptive therapy also differed from the case study. Therefore, we believe that our perceptual learning is an alternative TON training method. The enhanced visual function of our subjects might be explained by the fact that perceptual learning [24] might contribute to long-term changes in the sensory cortex [26], increase the efficiency of neural processing and network, increase visual nerve plasticity, trigger axonal regeneration [13 27], and prevent the disuse of visual function.

In the present study, we firstly reported two children with complete visual loss before and after EOND surgery regained light perception 2 months after rehabilitation. These findings indicated that the initial visual acuity recovery for severe TON subjects after EOND might occur approximately 2 months after optic nerve injury when SWD therapy combined with perceptual training was intervened several days after EOND surgery, especially for children. Better improvements in visual functions and VEP parameters after rehabilitation for younger individuals in our study might confirm the beneficial effects of rehabilitation for children with severe TON. Combined rehabilitation strategy for the children might more easily induce optic nerve axonal regeneration [28], consequently, resulting in partially returning to normal in structure and function of the severely injured optic nerve in a longer period, rather than 3-4 weeks for peripheral nerve regeneration, as described in the literature [29].

Previous studies have demonstrated that VEP was an objective indicator in predicting visual outcome after optic nerve injury, and P100 was the most stable and the highest amplitude component in VEP examination [30]. The increased P100 amplitude of the VEP might reflect optic function recovery after SWD therapy combined with perceptual training. Our result was inconsistent with the conclusions of Holmes[31] and Xie [32], whose studies indicated that visual recovery may be impossible when VEP results were not recordable within 7 days after injury or after EOND surgery. Our data indicated that, even though VEP results are not recordable in subjects with the complete visual loss after optic nerve injury and approximately 2 months after EOND surgery, visual function recovery might occur in children when the combined rehabilitation program was performed several days after surgery.

The fraction anisotropy is a highly sensitive biomarker of neuropathology and microstructural architecture in diffusion tensor imaging measurement, and is thought to quantitatively reflect pathological changes in fiber density, axonal diameter, and myelination in the white matter [33]. An increased fraction anisotropy value in injured optic nerve after rehabilitation and the positive associations between pre-rehabilitation fraction anisotropy value and post-rehabilitation visual functions indicated that fraction anisotropy value might predict visual function recovery after SWD therapy combined with perceptual training. The mean diffusivity and radial diffusivity values in injured optic nerve were increased after TON [34 35] and were reduced after rehabilitation. The increased fraction anisotropy and decreased mean diffusivity and radial diffusivity values might suggest that the axon and myelin sheath degenerations were partially reversed after rehabilitation [34]. Anterior axial diffusivity value was decreased 10 weeks after rehabilitation. This is inconsistent with the view of Bodanapally et al who considered low axial diffusivity value as a surrogate for axonal injury [36]. The reason for the lower anterior axial diffusivity value 10 weeks after rehabilitation remains unclear. Possible explanations include: 1) the difference of the time in the acquisition of diffusion tensor imaging since axial diffusivity value was the time-dependent changes [34]. In Bodanapally study, acquisition of diffusion tensor imaging was equal or less than15 days after trauma, other than more than 10 weeks after trauma in our study; 2) increased surrounding air in the cavities of nasal sinuses after surgery, and; 3) the severity of the subjects recruited in our study.

Our study has several limitations. First, the sample size is relatively small, and all included patients are from single-center with the same ethnicity and region, which might limit the generalization. Second, we only compared the recovery before and after perceptual training combined with SWD treatment in a single group, but neither established a control group, nor comparatively analyzed therapeutic effects between perceptual training and SWD in the patients with TON. Future studies with larger sample sizes and longer follow-up periods, and more groups are needed to validate and strengthen our present conclusion.

Conclusions

In summary, our study showed significant improvements in visual acuity and color vision following targeted SWD therapy combined with perceptual training after EOND surgery in patients with severe TON, and these findings suggested that the combined treatment strategies were effective in improving the visual functions in these patients.The VEP and diffusion tensor imaging parameters, which were correlated with the visual functions after rehabilitation, might be the predictors of potential visual function recovery. Additionally, the children with discontinued optic nerve in diffusion tensor imaging, un-recordable VEP, and complete visual loss for approximately two months after the operation regained visual function when combined rehabilitation was intervened several days after EOND surgery. These findings indicated that SWD therapy combined with perceptual training might trigger and increase the possibility of optic nerve axonal regeneration in children.

Declarations

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Authors' contributions

TQ had contributions to rehabilitation design and writing. ZH wrote the manuscript. ZQ, ZW, TM, and HZ collected data. TQ, ZH, and ZQ performed data analysis. JW and XZ designed the research study. All authors reviewed the manuscript and approved the final version.

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Availability of data and materials

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics approval and consent to participate

This study was performed in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Xiangya Hospital, Central South University (201607963), as well as by the Ethics Committee of Brain Hospital of Hunan Province, Hunan University of Chinese Medicine (K2016065). Written informed consent was obtained from all participants, parents or guardians.

Consent for publication

Not applicable

Competing interests

The Author(s) declare(s) that there is no conflict of interest.

References

1. Martinez-Perez R, Albonette-Felicio T, Hardesty DA, Carrau RL, Prevedello DM. Outcome of the surgical decompression for traumatic optic neuropathy: a systematic review and meta-analysis. Neurosurgical review 2021;**44**(2):633-41 doi: 10.1007/s10143-020-01260-z[published Online First: Epub Date]|.
2. Ropposch T, Steger B, Meco C, et al. The effect of steroids in combination with optic nerve decompression surgery in traumatic optic neuropathy. The Laryngoscope 2013;**123**(5):1082-6 doi: 10.1002/lary.23845[published Online First: Epub Date]|.

3. Tao Y, Chen T, Liu B, et al. The transcorneal electrical stimulation as a novel therapeutic strategy against retinal and optic neuropathy: a review of experimental and clinical trials. International journal of ophthalmology 2016;**9**(6):914-9 doi: 10.18240/ijo.2016.06.21[published Online First: Epub Date]|.
4. Sabel BA, Gao Y, Antal A. Reversibility of visual field defects through induction of brain plasticity: vision restoration, recovery and rehabilitation using alternating current stimulation. Neural regeneration research 2020;**15**(10):1799-806 doi: 10.4103/1673-5374.280302[published Online First: Epub Date]|.
5. Gall C, Schmidt S, Schittkowski MP, et al. Alternating Current Stimulation for Vision Restoration after Optic Nerve Damage: A Randomized Clinical Trial. PloS one 2016;**11**(6):e0156134 doi: 10.1371/journal.pone.0156134[published Online First: Epub Date]|.
6. Vaitheeswaran K, Kaur P, Garg S. Perceptual Learning for Rehabilitation in Traumatic Optic Neuropathy. Neuroophthalmology 2014;**38**(2):88-90 doi: 10.3109/01658107.2013.856450[published Online First: Epub Date]|.
7. Draper DO. Pulsed Shortwave Diathermy and Joint Mobilizations for Achieving Normal Elbow Range of Motion After Injury or Surgery With Implanted Metal: A Case Series. Journal of Athletic Training 2014;**49**(6):851-55 doi: 10.4085/1062-6050.49.3.45[published Online First: Epub Date]|.
8. Hyldahl RD, Hafen PS, Nelson WB, et al. Passive muscle heating attenuates the decline in vascular function caused by limb disuse. The Journal of physiology 2021;**599**(20):4581-96 doi: 10.1113/JP281900[published Online First: Epub Date]|.
9. Marotta N, Demeco A, Inzitari MT, Caruso MG, Ammendolia A. Neuromuscular electrical stimulation and shortwave diathermy in unrecovered Bell palsy: A randomized controlled study. Medicine 2020;**99**(8):e19152 doi: 10.1097/md.0000000000019152[published Online First: Epub Date]|.
10. Kashkouli MB, Yousefi S, Nojomi M, et al. Traumatic optic neuropathy treatment trial (TONTT): open label, phase 3, multicenter, semi-experimental trial. Graefe's archive for clinical and experimental ophthalmology = Albrecht von Graefes Archiv fur klinische und experimentelle Ophthalmologie 2018;**256**(1):209-18 doi: 10.1007/s00417-017-3816-5[published Online First: Epub Date]|.
11. Emanuelli E, Bignami M, Digilio E, Fusetti S, Volo T, Castelnuovo P. Post-traumatic optic neuropathy: our surgical and medical protocol. European archives of oto-rhino-laryngology : official journal of the European Federation of Oto-Rhino-Laryngological Societies (EUFOS) : affiliated with the German Society for Oto-Rhino-Laryngology - Head and Neck Surgery 2015;**272**(11):3301-9 doi: 10.1007/s00405-014-3408-5[published Online First: Epub Date]|.
12. Zhengquan Y, Feng L, Denggao W, Yong W, Ping Z, Zhiping L. Study on Effect of Very High Frequency Vadiation(VHF) on Nerve System Function. China Public Heath 2002;**18**(9):1066-67 doi: 10.3321/j.issn:1001-0580.2002.09.022[published Online First: Epub Date]|.
13. Dosher B, Lu Z-L. Visual Perceptual Learning and Models. In: Movshon JA, Wandell BA, eds. Annual Review of Vision Science, Vol 3, 2017:343-63.
14. Schulze-Bonsel K, Feltgen N, Burau H, Hansen L, Bach M. Visual acuities "hand motion" and "counting fingers" can be quantified with the freiburg visual acuity test. Investigative ophthalmology & visual science 2006;**47**(3):1236-40 doi: 10.1167/iovs.05-0981[published Online First: Epub Date]|.
15. Lee J-Y, Cho K, Park K-A, Oh SY. Analysis of Retinal Layer Thicknesses and Their Clinical Correlation in Patients with Traumatic Optic Neuropathy. Plos One 2016;**11**(6) doi: 10.1371/journal.pone.0157388[published Online First: Epub Date]|.
16. Gao Y, Li J, Ma H, et al. The retinal vasculature pathophysiological changes in vision recovery after treatment for indirect traumatic optic neuropathy patients. Graefe's archive for clinical and experimental ophthalmology = Albrecht von Graefes Archiv fur klinische und experimentelle Ophthalmologie 2021;**259**(10):3093-105 doi: 10.1007/s00417-021-05208-x[published Online First: Epub Date]|.
17. Incebiyik S, Boyaci A, Tutoglu A. Short-term effectiveness of short-wave diathermy treatment on pain, clinical symptoms, and hand function in patients with mild or moderate idiopathic carpal tunnel syndrome. Journal of Back and Musculoskeletal Rehabilitation 2015;**28**(2):221-28 doi: 10.3233/bmr-140507[published Online First: Epub Date]|.
18. Ye D, Chen C, Wang L, Shen M. Short-wave therapy for spontaneous pneumothorax: A case report. Bioelectromagnetics 2017;**38**(1):78-81 doi: 10.1002/bem.22013[published Online First: Epub Date]|.
19. Sousa NTA, Guirro ECO, Calió JG, Queluz MC, Guirro RRJ. Application of shortwave diathermy to lower limb increases arterial blood flow velocity and skin temperature in women: a randomized controlled trial. Brazilian journal of physical therapy 2017;**21**(2):127-37 doi: 10.1016/j.bjpt.2017.03.008[published Online First: Epub Date]|.
20. Vardiman JP, Moodie N, Siedlik JA, Kudrna RA, Graham Z, Gallagher P. Short-Wave Diathermy Pretreatment and Inflammatory Myokine Response After High-Intensity Eccentric Exercise. Journal of Athletic Training 2015;**50**(6):612-20 doi: 10.4085/1062-6050-50.1.12[published Online First: Epub Date]|.
21. Xie C, Li X, Fang L, Wang T. Effects of Athermal Shortwave Diathermy Treatment on Somatosensory Evoked Potentials and Motor Evoked Potentials in Rats With Spinal Cord Injury. Spine (Phila Pa 1976) 2019;**44**(13):E749-E58 doi: 10.1097/BRS.0000000000002980[published Online First: Epub Date]|.

22. Scott BO. Effects of contact lenses on short-wave field distribution. The British journal of ophthalmology 1956;**40**(11):696-7 doi: 10.1136/bjo.40.11.696[published Online First: Epub Date]|.
23. Zhongli W, Xiuhua Y, Yangyang L, et al. Effects of ultra-shortwave irradiation on the expression of the apoptosis-related genes Bcl-2 and Bax in the lens epithelial cells of the eye. Chin J Phys Med Rehab 2014;**36**(12):913-17 doi: 10.3760/cma.j.issn.0254-1424.2014.012.004[published Online First: Epub Date]|.
24. Law CL, Backus BT. Use of a new composite index to demonstrate improved stereoacuity after training on stimuli with dichoptically asymmetric contrast. Vision Research 2020;**171**:73-83 doi: 10.1016/j.visres.2019.10.005[published Online First: Epub Date]|.
25. Gori M, Mazzilli G, Sandini G, Burr D. Cross-Sensory Facilitation Reveals Neural Interactions between Visual and Tactile Motion in Humans. Frontiers in psychology 2011;**2**:55 doi: 10.3389/fpsyg.2011.00055[published Online First: Epub Date]|.
26. Yan Y, Rasch MJ, Chen M, et al. Perceptual training continuously refines neuronal population codes in primary visual cortex. Nature Neuroscience 2014;**17**(10):1380-87 doi: 10.1038/nn.3805[published Online First: Epub Date]|.
27. Horton JC, Fahle M, Mulder T, Trauzettel-Klosinski S. Adaptation, perceptual learning, and plasticity of brain functions. Graefes Archive for Clinical and Experimental Ophthalmology 2017;**255**(3):435-47 doi: 10.1007/s00417-016-3580-y[published Online First: Epub Date]|.
28. Li J, Zhang Z, Wang J, et al. Protein Kinase Cα Promotes Proliferation and Migration of Schwann Cells by Activating ERK Signaling Pathway. Neuroscience 2020;**433**:94-107 doi: 10.1016/j.neuroscience.2020.03.007[published Online First: Epub Date]|.
29. Scheib J, Höke A. Advances in peripheral nerve regeneration. Nature reviews. Neurology 2013;**9**(12):668-76 doi: 10.1038/nrneurol.2013.227[published Online First: Epub Date]|.
30. Gao Y, Li J, Ma H, et al. Endoscopic trans-ethmosphenoid optic canal decompression is an optimal choice to save vision for indirect traumatic optic neuropathy. Acta ophthalmologica 2021 doi: 10.1111/aos.14951[published Online First: Epub Date]|.
31. Holmes MD, Sires BS. Flash visual evoked potentials predict visual outcome in traumatic optic neuropathy. Ophthalmic Plast Reconstr Surg 2004;**20**(5):342-6 doi: 10.1097/01.iop.0000134272.55294.4c[published Online First: Epub Date]|.
32. Xie D, Yu H, Ju J, Zhang L. The Outcome of Endoscopic Optic Nerve Decompression for Bilateral Traumatic Optic Neuropathy. Journal of Craniofacial Surgery 2017;**28**(4):1024-26 doi: 10.1097/scs.0000000000003743[published Online First: Epub Date]|.
33. Wu CN, Duan SF, Mu XT, et al. Assessment of optic nerve and optic tract alterations in patients with orbital space-occupying lesions using probabilistic diffusion tractography. International journal of ophthalmology 2019;**12**(8):1304-10 doi: 10.18240/ijo.2019.08.11[published Online First: Epub Date]|.
34. Li J, Shi W, Li M, et al. Time-dependent diffusion tensor changes of optic nerve in patients with indirect traumatic optic neuropathy. Acta radiologica (Stockholm, Sweden : 1987) 2014;**55**(7):855-63 doi: 10.1177/0284185113506900[published Online First: Epub Date]|.
35. Yang QT, Fan YP, Zou Y, et al. Evaluation of traumatic optic neuropathy in patients with optic canal fracture using diffusion tensor magnetic resonance imaging: a preliminary report. ORL J Otorhinolaryngol Relat Spec 2011;**73**(6):301-7 doi: 10.1159/000330723[published Online First: Epub Date]|.
36. Bodanapally UK, Kathirkamanathan S, Geraymovych E, et al. Diagnosis of Traumatic Optic Neuropathy: Application of Diffusion Tensor Magnetic Resonance Imaging. Journal of Neuro-Ophthalmology 2013;**33**(2):128-33 doi: 10.1097/WNO.0b013e3182842553[published Online First: Epub Date]|.

Tables

Table 1. DTI parameter in traumatic optic nerve

Parameters	Anterior			Middle			Posterior		
	Postoperation	Postreatment		Postoperation	Postreatment		Postoperation	Postreatment	
	Mean±SD	Mean±SD	T	Mean±SD	Mean±SD	T	Mean±SD	Mean±SD	T
DTI									
FA	0.24±0.09	0.33±0.13	-2.82*	0.36±0.09	0.38±0.07	-1.33	0.39±0.06	0.40±0.06	-0.78
ADC (10^{-3}mm 2 /s)	1.92±0.48	1.47±0.54	3.29**	1.26±0.26	1.13±0.25	2.16*	1.17±0.27	1.16±0.23	0.41
AD	2.43±0.54	1.96±0.65	2.61*	1.75±0.36	1.48±0.26	3.60**	1.68±0.21	1.58±0.32	1.44
RD	1.68±0.47	1.24±0.51	3.28*	0.99±0.28	0.99±0.27	0.23	0.90±0.26	0.97±0.16	-0.79

AD = axial diffusivity; ADC = mean diffusivity; DTI = diffusion tensor imaging; FA = fractional anisotropy; Postreatment = 10 weeks after rehabilitation; RD = radial diffusivity; *P < .05; **P < .01;.

Table 2. Clinical parameters of BCVA, color vision and VEP in injured eye

Parameters	Preoperation Mean±SD	Postoperation Mean±SD	Postreatment 1 Mean±SD	Postreatment 2 Mean±SD	Value
BCVA (logMAR)	3.00±0.00	2.69±0.40	1.89±0.82	1.44±0.91	F=33.77**
Color vision	0.00±0.00	0.00±0.00	5.39±8.31	9.00±11.32	F=9.72**
VEP					
P100 latency (ms)		23.30±45.14	106.88±47.83		T=-5.82**
P100 amplitude (μV)		0.71±2.27	4.27±4.09		T=-3.24**

BCVA = Best corrected visual acuity; Color vision (correct answers/a set of plates); Postreatment 1 = 10 weeks after rehabilitation; Postreatment 2 = 16 weeks after rehabilitation; VEP = Visual evoke potential; *P < .05, ** P < .01.

Table 3. DTI parameter in traumatic optic nerve

Parameters	Anterior			Middle			Posterior		
	Postoperation	Postreatment		Postoperation	Postreatment		Postoperation	Postreatment	
	Mean±SD	Mean±SD	T	Mean±SD	Mean±SD	T	Mean±SD	Mean±SD	T
DTI									
FA	0.24±0.09	0.33±0.13	-2.82*	0.36±0.09	0.38±0.07	-1.33	0.39±0.06	0.40±0.06	-0.78
ADC (10^{-3}mm 2 /s)	1.92±0.48	1.47±0.54	3.29**	1.26±0.26	1.13±0.25	2.16*	1.17±0.27	1.16±0.23	0.41
AD	2.43±0.54	1.96±0.65	2.61*	1.75±0.36	1.48±0.26	3.60**	1.68±0.21	1.58±0.32	1.44
RD	1.68±0.47	1.24±0.51	3.28*	0.99±0.28	0.99±0.27	0.23	0.90±0.26	0.97±0.16	-0.79

AD = axial diffusivity; ADC = mean diffusivity; DTI = diffusion tensor imaging; FA = fractional anisotropy; Postreatment = 10 weeks after rehabilitation; RD = radial diffusivity; *P < .05; **P < .01.

Figures

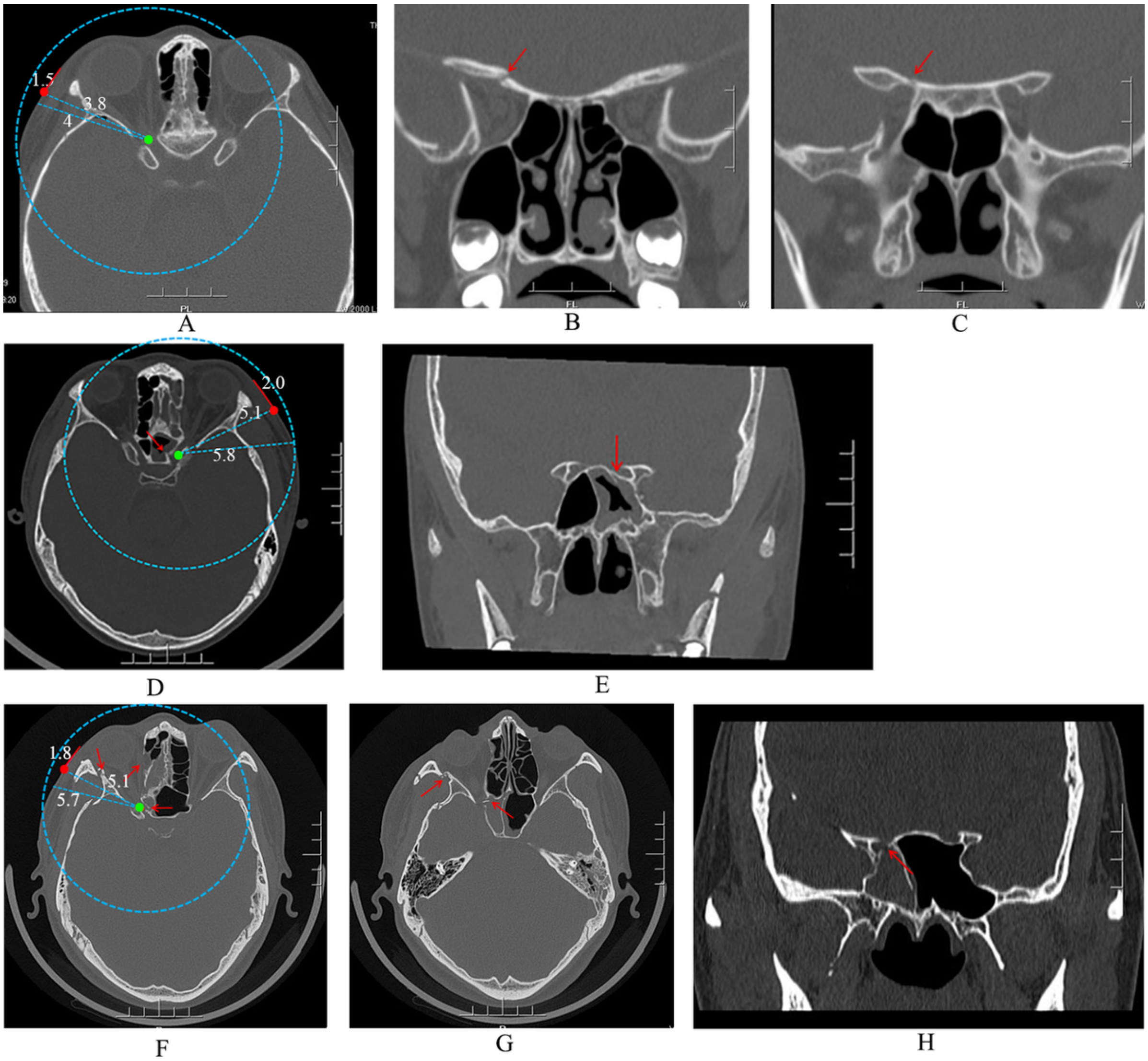

Figure 1

Location of the fracture and the injured optic nerve using high-resolution CT. A circle was made around the injured nerve to identify the skin areas where one electrode of the shortwave was placed on. (A-C) images represent fractures in a 6-year-old subject (Case 1). (A) Injured optic nerve in the area of the right orbital apex (green dot). The point of the skin (red dot) in the ipsilateral temporal area was placed at one electrode of the shortwave. (B) Fracture in the superior wall of the orbit in the coronal plane of the high-resolution CT scan (red arrow). (C) Fracture in the superior wall of the orbital apex in the coronal plane of CT scan (red arrow). (D-E) images represent fractures of a subject aged 13 years (Case 6). (D) Injured optic nerve in the area of the left optic canal (green dot). Fracture in the left medial wall of the optic canal in horizontal plane of CT scan (red arrow). Red dot represented the center of the electrode. (E) Fracture in the medial wall of the optic canal in coronal plane of CT scan (red arrow). (F-H) Images represent fractures of a subject aged 30 years (Case 11). (F) Injured optic nerve in the area of the right optic canal (green dot). Fracture in right medial and lateral wall of the orbit and medial wall of the optic canal in horizontal plane of CT scan (red arrow). Red dot represented the center of the electrode. (G) Fracture in lateral wall of the orbit and medial wall of the orbital apex in coronal plane of CT scan (red arrow). (H) Fracture in the medial wall of the optic canal in coronal plane of CT scan (red arrow).

Figure 2

Shortwave diathermy therapy. One circular electrode was applied in the ipsilateral temporal area of the injured nerve identified by a three-dimensional alignment procedure through high-resolution CT scan. Another circular electrode was applied in the ipsilateral frontal area of the injured nerve. The distance between these two electrodes was approximately 2.5 cm, and the distance between the electrode and the skin was 2 cm.

Figure 3

Perceptual training. (A) Light stimulation. (B) Differentiation of the shapes and objects with pictures. (C) Differentiation of shapes and objects with real objects. (D) Differentiation of written words. (E) Color vision training. (F) Constraint-induced perceptive therapy with eye patch wearing on the intact eye.

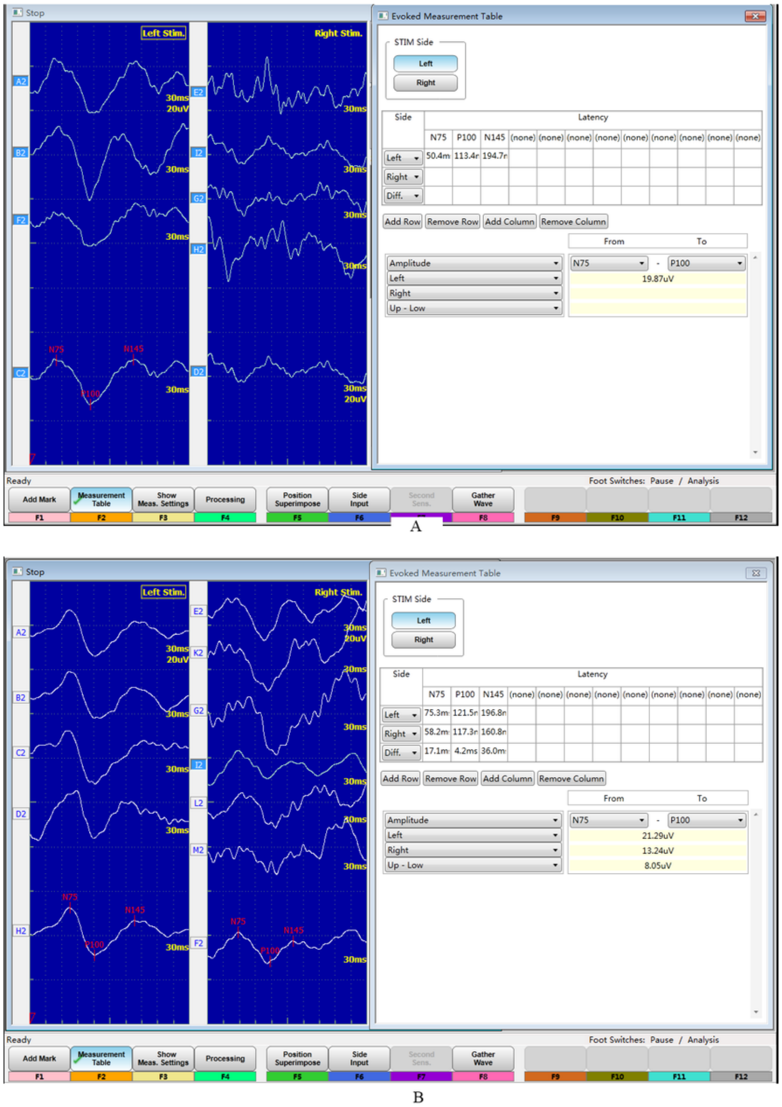

Figure 4

VEP images obtained from a subject aged 10 years (Case 5) with a right injured optic nerve. (A) the latency and amplitude of the P100 wave of the optic nerve in VEP testing 58 days after optic nerve injury. The image showed that P100 waves of right injured optic nerve were not detected, and P100 waves of left intact optic nerve were detected with an average P100 amplitude of 19.87 μv and an average P100 latency of 113.4 ms. (B) the latency and amplitude of the P100 wave of the optic nerve in VEP testing approximately 4 months after rehabilitation. This image showed that P100 waves of bilateral optic nerve were detected with an average P100 amplitude of 13.24 μv and an average P100 latency of 117.3 ms in right injured optic nerve, and with an average P100 amplitude of 21.29 μv and an average P100 latency of 121.5 ms in left intact optic nerve.

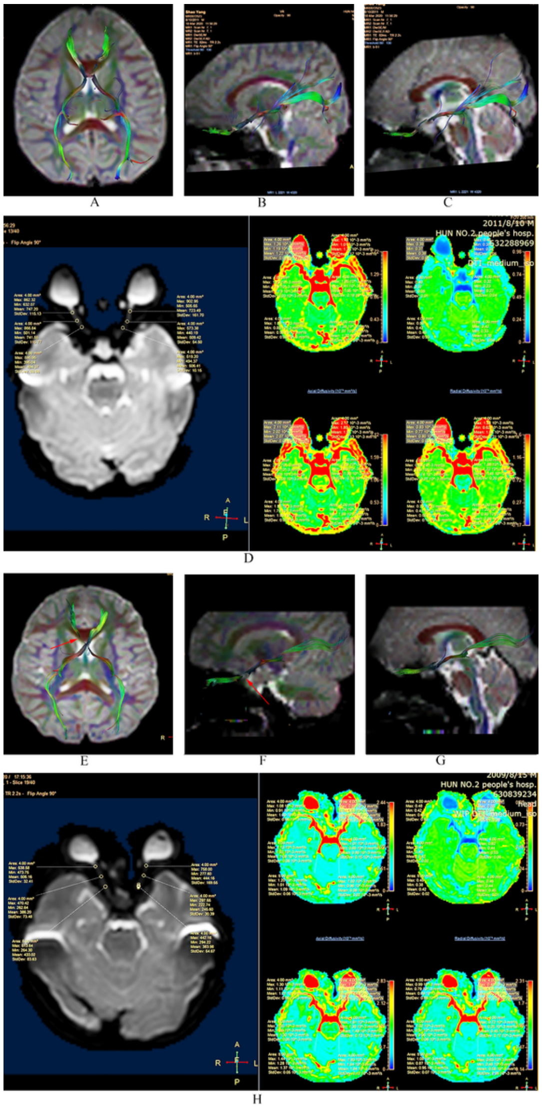

Figure 5

Diffusion tensor imaging images of the visual pathways. (A-C) horizontal, right sagittal and left sagittal diffusion tensor imaging images in an 8-year-old boy with the left injured optic nerve (case 2). The visual acuity of the subject improved from a score of 1.85 logMAR postoperatively to 0.4 logMAR approximately 16 weeks after rehabilitation. These images indicated that left optic nerve fibers were sparse and obviously less abundant than right optic nerve fibers. (E-G) horizontal, right sagittal and left sagittal diffusion tensor imaging images with right injured optic nerve (case 5). The visual acuity of the subject improved from a score of 3.0 logMAR postoperatively to 0.7 logMAR approximately 16 weeks after rehabilitation. These images indicated that right optic nerve fibers were discontinued (red arrow). (D) Case 2 and (H) Case 5 images representing the regions of interest (ROIs) were placed at the central section of the optic nerve segments (anterior, middle and posterior) on the b0 averaged magnified horizontal image, and the ADC, FA, AD and RD of optic nerve were calculated using the Philips intellispace portal. ADC = apparent diffusion coefficient; AD = axial diffusivity; BCVA = best-corrected visual acuity; FA= fraction anisotropy; RD = radial diffusivity.

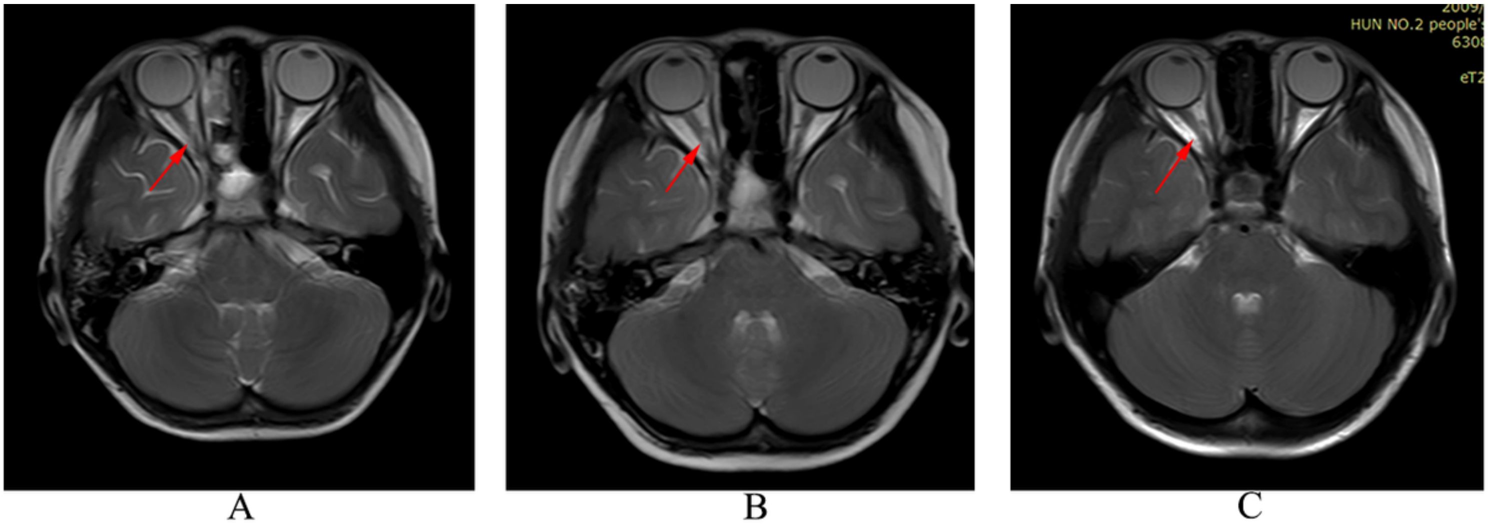

Figure 6

MRI images of the optic nerve. (A-C) a 10-year-old boy with a right injured optic nerve in the rehabilitation (Reh) group (case 5). (A) the optic nerve 12 days after injury (9 days after surgery). MRI indicated that the optic nerve had slight edema, and the red arrow pointed to the injured nerve that was displaced and had axonal degeneration. (B) the optic nerve 52 days after injury. The red arrow pointed to the injured nerve that had axonal degeneration. (C) the optic nerve 117 days after injury. Axonal regeneration occurred in partially injured optic nerve (red arrow).

Supplementary Files

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