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Original Article

Navigating precision: Anatomical insights into the efficacy of masks versus stereotactic frames in icon gamma knife treatment for trigeminal neuralgia

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ABSTRACT

Background: The trigeminal nerve is approximately 2 mm in thickness. Its location is critical due to the alignment of the brain stem. Hence, precise fixation during the gamma knife (GK) treatment is particularly important. This study aimed to compare the effectiveness of mask fixation compared to frame fixation during the irradiation of trigeminal neuralgia (TN) treatment.

Methods: A prospective clinical study involving 135 patients with essential TN in Baghdad, Iraq, was conducted from January to July 2024. The study used two head fixation methods: stereotactic frames and plastic masks. Patients were treated with an Icon version of the GK, with no previous radiation treatment. Patients were diagnosed with 3 Tesla magnetic resonance imaging and assessed using the Barrow Neurological Institute (BNI) score before treatment. Clinical response was assessed at 3-month intervals. Ethical consent was obtained from all patients involved.

Results: This study analyzed the socio-demographic parameters of patients with TN and found that females were more prevalent. 5.2% of patients underwent glycerol injection, while 2.9% underwent microvascular decompression surgery. The BNI score was formulated for fixation methods, with frame fixation with screws and local anesthesia reaching IV and V scores. The response of TN patients to GK treatment was assessed using the BNI score before and after three months. Most patients showed pain relief, with 17.9% having a complete response. A Chi-square statistical analysis showed no significant difference between frame and mask fixation.

Conclusion: There was no significant difference in the precision of frame fixation compared to the plastic mask fixation for TN. The mask is as efficient as the frame.

Keywords: Gamma knife, Mask, Neuroanatomical perspectives, Stereotactic frame, Trigeminal neuralgia

INTRODUCTION

The trigeminal nerve, the largest of the five cranial nerves, divides into the ophthalmic, maxillary, and mandibular branches. Mastication and pain blocking are facilitated by the facial and motor sensory signals supplied by this nerve.[7] TN is a very painful disease described as electric pulses or shock-like episodes every about 1 sec to 2 minutes. It occurs whether unilateral or rarely bilateral disease.[3] The first line of TN treatment is medication such as Carbamazepine, Oxcarbazepine, Gabapentin, Baclofen, Clonazepam, Estrogen, Topiramate, tramadol, and nonsteroidal anti-inflammatory drugs. The second line of treatment is surgery, such as microvascular decompression (MVD), rhizotomy, and peripheral pain block to the nerve.[2] The gamma knife (GK) is a radiosurgical procedure that contains 192 radioactive sources of cobalt 60 (CO-60). It is used to treat malignant and benign tumors and functional disorders like TN, as approved by the FDA.[11,12,15,16]

Due to the fixed nature of the GK collimator, the patient must maintain head alignment throughout the treatment. From its inception until the Perfexion version, the stereotactic Leksell frame was the primary means of head fixation in the GK.[1] The frame is fixed in the head by the screws after local anesthesia injection causing harmful feelings to the patients. In the Icon version, a cone beam computed tomography (CBCT) was installed to improve the treatment's accuracy. This allowed us to use the plastic mask.[6] Because of the small, targeted area of the trigeminal nerve and the critical organs, such as the brain stem near the nerve, more focus must be performed during the treatment. Most neurosurgeons worldwide are afraid to use the mask instead of the frame in GK for trigeminal neuralgia (TN). This study aimed to assess and compare the efficiency of treating patients with TN with the fixation method of frame versus the mask.

MATERIALS AND METHODS

This is a prospective clinical study with a purposive sampling technique performed from January to July 2024 in Saad Al-Witry Hospital for Neurosciences and in Al-Taj Center for GK, Baghdad, Iraq. This study involved 135 patients with essential TN. This study used two head fixation methods: a stereotactic frame and a plastic mask. Sixty-four patients were fixed with frames, and seventy-one patients were fixed with masks. Those who fixed the frame were injected with local anesthesia in four pleases of the screws. The patients were treated with an Icon version of the GK at Saad Al-Witry Hospital for Neurosciences and Al-Taj Center, Baghdad, Iraq. The inclusion criteria are patients with essential TN rated as IV or V scale of Barrow Neurological Institute (BNI) score[13] and treated with a dose of 80 Gy with no previous radiation treatment. The exclusion criteria are patients treated with different doses, those with brain tumors, or those who previously had any treatment. All patients were diagnosed with 3 Tesla magnetic resonance imaging (MRIs) before treatment.

The MRI sequences are as follows: the first one is the T1w 3D Turbo field echo (TFE)-Transverse sequence contains the following parameters: voxel size = 1.0 × 1.0 × 1.0 mm slab 1, slices per slab = 176, slice thickness = 1 mm, distance factor = 50%, phase encoding = Right-Left (phase encoding direction)(RL), phase oversampling = 0%, slice oversampling = 45.5%, Field of view (FOV) = read 256 mm, FOV phase = 81.3%, Repetition time (TR) = 2030 ms, Echo time (TE) = 3.7 ms, averages = 1, and concatenations = 1. The second sequence is T2-weighted turbo spin echo (T2w TSE) sagittal: this sequence was set in sagittal plane as the following parameters: voxel size = 0.9 × 0.9 × 0.9 mm, slab = 1, slice per slab = 60, slice thickness = 0.9 mm, distance factor = 20%, phase encoding = RL, phase over sampling = 0%, slice oversampling = 6.7%, FoV = read 230 mm, FoV phase = 90.6%, TR = 5.54 ms, TE = 2.47 ms, and averages = 2.

All patients were assessed in BNI score before the GK treatment either to have IV or V score. The prescribed dose for these patients was 80 Gy.

Then, the high-definition motion management (HDMM) technology in the GK Icon version is used with a mask incorporation with infrared reflective markers that are placed on the patient nose to detect the motion deviation at a certain threshold. This technology is used to ensure precision in targeting the tumor. The threshold used in this study is 1.5 mm. A robust QA program is essential to verify the performance of HDMM. Typical QA protocols include periodic calibration of motion detection sensors, testing the accuracy of the HDMM system, and possibly phantom studies to simulate patient motion scenarios. Documentation of the frequency and methods of QA checks, including any inter-session verifications, is critical to ensure that the system is consistently functioning within specified tolerances. The treatment duration for patients with TN varied for each patient; it ranged from 30 to 45 min with a mean ± SD is 37.32 ± 10.99 min. During the treatment, five patients exceeded the threshold of head movement, so they were excluded from this study. Exceeding the motion thresholds negatively affects the accuracy and precision of GK treatments, as the patient's movement may cause unwanted radiation delivery.

After that, CBCT is used for patient fixation by fusing the image with MRI planning images. The process of image fusion protocol, particularly for high-precision cases of TN when fusing CBCT and MRI images, begins with careful patient positioning and immobilization using a securely fitted mask performed by selecting MRI images, which is preferred for capturing high-resolution soft-tissue details, while CBCT, obtained directly on the GK Icon, to provide a clear view of bony anatomy. MRI sequences are chosen for minimal distortion, such as 3D T1-weighted images, and special considerations may be applied to visualize structures like cranial nerve V. Following image acquisition, the GK Icon software performs an initial automated fusion of CBCT and MRI images. This is then manually verified and adjusted by aligning key anatomical landmarks, especially in critical areas. The allowable margin of error during the treatment setup was set to 0.5 mm or less to ensure precise targeting. Quality assurance measures include periodic phantom-based verifications to confirm the system's fusion accuracy, typically conducted quarterly or following any software updates. In addition, pretreatment verification by a secondary reviewer ensures the fusion's accuracy within the intended target region. This detailed approach allows for consistent precision in treatment setup, providing a comprehensive foundation for safe and effective GK Icon procedures.

The clinical response was assessed in fixed time intervals, which is 3 months. Each patient in this study signed a written ethical consent after clarifying the details and purpose. The statistical analysis was performed using SPSS version 38 at a significant level equal to 0.05 or less.

Anatomical landmarks in frame and mask fixation for GK radiosurgery (GKRS)

Precise GKRS in TN requires accurate anatomical positioning. It can be performed by basing fixation on either a stereotactic frame or a plastic mask, using anatomical landmarks to guide accurate targeting of the nerve and avoid injury to adjacent critical structures.

The stereotactic frame is immobilized by the insertion of four pins into selected cranial landmarks. These sites are selected based on their ability to offer rigid anchorage in an attempt to limit patient head movement during treatment [Figure 1].

- Frontal Bone: Fixation on the frontal bone is commonly done with two points since it contains heavy cortical bone; pin placement in this bone provides effective fixation and has a low risk of deformation. The area is ideal for anchoring the frame because it provides minimum head displacement and increases targeting accuracy during treatment for TN.[13]
- Occipital Bone: Two more pins would be placed in the occipital bone. Similar to the frontal bone, it provides a thick, stable surface for fixation. This position provides a secure posterior anchorage, which minimizes the possibility of head movement. Significantly, the robust structure of the occipital region allows reliable fixation of the frame with a very low probability of movement that could alter the accuracy of radiation delivery.[6]
- Temporal Fossa: This is another landmark, lateral to the orbit and posterior to the zygomatic arch, utilized in frame fixation. Although the pins are not placed directly into this area, they play a role during positioning and aligning the frame with regard to the trigeminal nerve to ensure optimal targeting during radiosurgery.[10]

In mask fixation, immobilization of the head of the patient is done using a molded plastic mask fitted to the contours of the face and head. Although this is much less invasive compared with frame fixation, the mask method relies on careful anatomic positioning to ensure that the head remains restriction-free during the procedure [Figures 2-4].

- Nasion: The point of intersection of the frontal and nasal bones, the nasion has remained an important anterior landmark for mask position. Proper alignment at the nasion will ensure that the mask fits snugly and maintains the head's stability during treatment.[8]
- Orbital Rims: The superior and lateral rims of the orbital cavity provide additional mask fitting with other important anatomical references. These contacts will serve to position the mask symmetrically and correctly, minimizing the opportunity for rotational displacement during the procedure. The contours that a natural

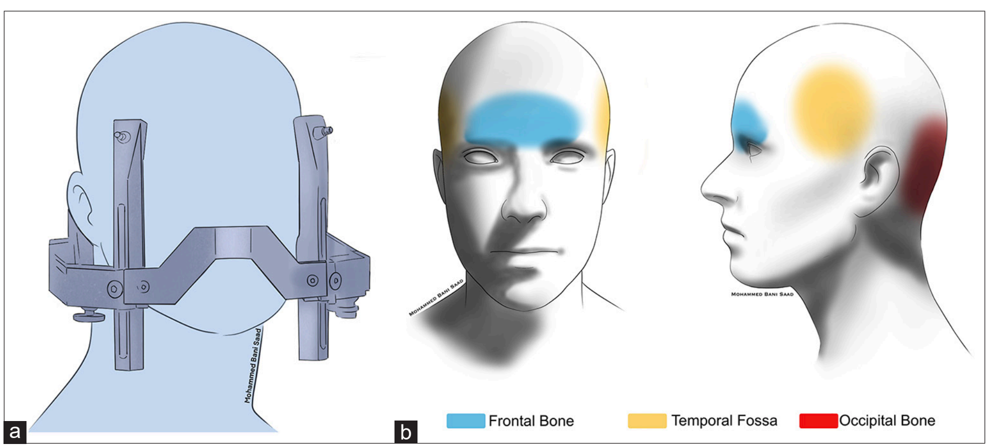

Figure 1: (a) The following is an illustration of the stereotactic frame that is applied in Gamma Knife radiosurgery. This frame is fixed with four pins: two in the frontal bone and two in the occipital bone. For rigid immobilization. This will ensure that there will not be any movement of the head while undergoing the treatment. (b) This is an image that highlights all the important anatomical landmarks with respect to frame fixation. These regions ensure that the head is securely stabilized, thus allowing accurate radiation delivery to the trigeminal nerve without affecting other surrounding structures.

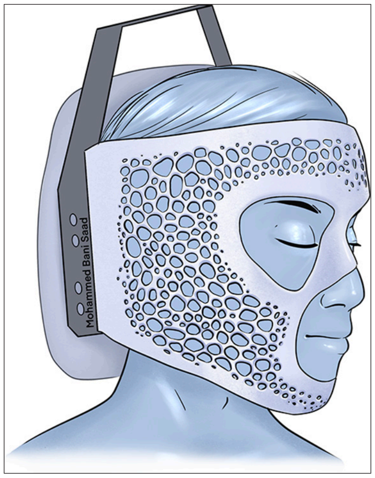

Figure 2: This figure illustrates the use of a custom-molded plastic mask for head fixation in gamma knife radiosurgery. Key anatomical landmarks such as the nasion, zygomatic arch, and external auditory meatus are utilized for secure fitting, providing stable head positioning. This method eliminates the need for invasive pins while maintaining precision for targeting the trigeminal nerve.

Figure 3: It shows a female patient with trigeminal neuralgia treated with a gamma knife by mask. It should be noticed that the marker on a patient's nose is made from stainless steel because it has minimal interference with infrared tracking.

orbital rim would provide assist in stabilizing the mask in place.[17]

- Zygomatic Arch: The zygomatic arch is a good lateral anchor, especially in the lower half of the mask. Ensuring this part of the mask is tightened around the zygomatic area will impede lateral shifting and thus ensure precision throughout radiosurgery.[5]
- External Auditory Meatus: The external auditory meatus represents a helpful lateral anatomical landmark that

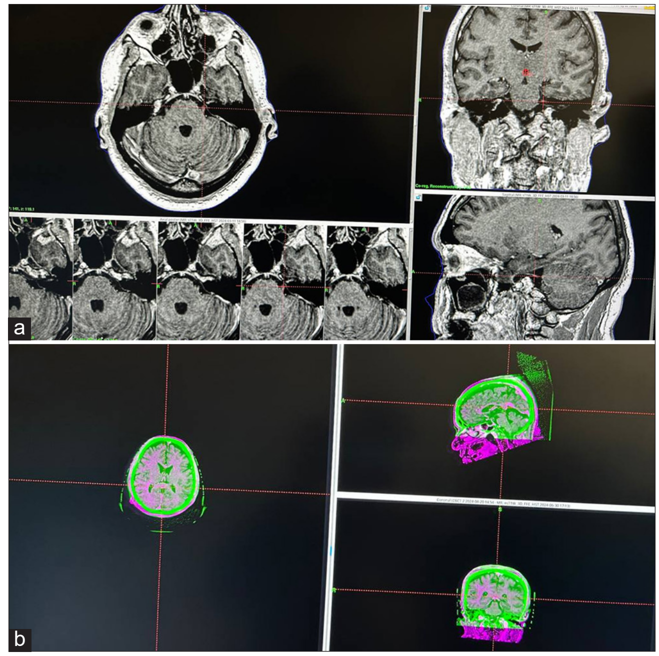

Figure 4: (a) Axial, coronal, and sagittal views illustrating the initial steps of image fusion during stereotactic treatment planning. The red markers highlight key anatomical structures used for alignment and reference. (b) Advanced fusion process integrating magnetic resonance imaging and computed tomography imaging. The green and magenta overlays demonstrate precise alignment, ensuring accurate targeting of the trigeminal nerve for gamma knife treatment.

serves as a guide for proper rotation and alignment of the mask. When properly fitted, the alignment near this landmark will maintain the head's rotational position, an important consideration when treating the trigeminal nerve, which lies proximal to both the brainstem and critical vascular structures.[14]

Both fixation methods are heavily reliant on the correct identification and utilization of anatomical landmarks. Due to the proximity of the trigeminal nerve to the brainstem, cranial nerves, and major arteries, slight misalignments in fixation may yield significant complications. Fixation by a stereotactic frame provides the added advantage of rigid stability, which is especially advantageous in patients whose structure of the cranial bone is not very robust. At present, however, the plastic mask has become comparably effective with the development of advanced imaging modalities such as CBCT that offer a less invasive alternative without compromising the precision required for GKRS.

RESULTS

The socio-demographic parameters results for the patients included in this study are listed in Table 1. The prevalence of females is shown to be higher in males. The questionnaire assessment showed that 7 (5.2%) of patients underwent glycerol injection, and 4 (2.9%) of patients underwent MVD surgery.

The BNI score was formulated for those who underwent the fixation method. The results of the BNI score for those who underwent the stereotactic frame fixation method were compared to those who underwent the mask fixation method, as shown in Table 2. It was shown that those who underwent the frame fixation method with screws and local anesthesia reached IV and V scores, while those with frame-only heat sensation and fixation were observed in 20% of patients.

The response of TN patients to the treatment of GK was assessed using the BNI score before and after three months of the treatment. The patients' responses fixed with frame were presented in Table 3. It was shown that most patients showed pain relief and rated as II score (64%), while 17.9% out of them were shown to have complete response to the treatment. Seven (10.2%) patients are rated as III score. Only 5 (7.9%) patients who scored a V grade were shown a little relief and shifted to the fourth score.

The BNI score assessment for those TN patients who were fixed with a plastic mask during the GK treatment was presented in Table 4. The assessment results before and after three months are those fixed within the frame. With a P = 0.943265, a Chi-square statistical analysis failed to detect a significant difference between frame and mask fixation.

Table 1: The socio-demographic of trigeminal neuralgia patients.

Socio-demographic	
Age (Years)	43.22±11.32 (20–73)
Range of symptoms (Months)	17.22±5.32 (4–48)
Gender	
Male	48 (35.6%)
Female	87 (64.4%)
Previous treatment	
Glycerol injection	7 (5.2%)
MVD surgery	4 (2.9%)

MVD: Microvascular decompression

Table 2: The difference in BNI pain score response between frame and mask.

Fixation method	I	II	III	IV	V
Frame (%)	0	24 (37.5)	25 (39.1)	10 (15.6)	5 (7.8)
Mask (%)	56 (80)	14 (20)	0	0	0

BNI: Barrow Neurological Institute

Table 3: Response of gamma knife treatment for trigeminal neuralgia using the stereotactic frame.

	I	II	III	IV	V
Pre-GKRS (%)	0	0	0	27 (42.2)	37 (57.8)
Post-months (%)	11 (17.9)	41 (64)	7 (10.2)	5 (7.9)	0

GKRS: Gamma knife radiosurgery

DISCUSSION

A virtual frame of reference is essential in mask-based Stereotaxy, validated using intraprocedural radiography imaging and registration to a reference patient geometry. This frame of reference rigidly connects the target and treatment equipment. This incision-free technique enables painless radiosurgery, eliminates the need for anesthesia and sterile treatments, and, most significantly, reduces the degree to which patients must be closely monitored using frame-based methods. This study showed that most patients showed pain relief and rated an II score (64%), while 17.9% had a complete response. The BNI score assessment for patients fixed with a plastic mask showed no significant difference between the two fixation methods. The study highlights the importance of careful consideration when using the GK for treating TN.

The trigeminal nerve arises from the lateral surface of the pons and crosses the prepontine cistern toward the trigeminal ganglion, which lies in Meckel's cave. Such a ganglion divides into three branches: ophthalmic (V1), maxillary (V2), and mandibular (V3) nerves. Anatomically, the trigeminal nerve is closely related to critical structures such as the brainstem and basilar artery, making precise targeting mandatory during the GK treatment to avoid collateral damage.[7] This dural pouch hosts the trigeminal ganglion and is usually situated in the middle cranial fossa, lying close to a petrous part of the temporal bone. The proximity of Meckel's cave to the cavernous sinus and the internal carotid artery requires careful planning during radiosurgery with mask fixation because slight misalignments can result in inadvertent radiation exposure to these important structures.[4]

In most circumstances, the stereotactic frame is fixed by four pins inserted into the frontal and occipital bones. These sites are chosen because the bones are thick and cortical, providing a secure point of attachment for the frame. The press applied by the pins can locally deform the skull, particularly in patients with generally thinner cranial bones, and thus may degrade targeting accuracy.[8] The screws for fixation in a frame perforate the scalp and even the periosteum, possibly causing some complications, including scalp hematomas or even infections. This could also lead to increased discomfort and anxiety in patients, which could reduce the ability of a patient to remain still during the procedure. Thus, the integrity of the anatomical scalp and underlying tissue is another important consideration when considering a choice between frame and mask fixation.[14]

Table 4: Response of gamma knife treatment for trigeminal neuralgia using the plastic mask.

Response	I (%)	II (%)	III (%)	IV (%)	V (%)	*P*-Value
Pre-GKRS (%)	0	0	0	27 (42.2)	37 (57.8)	0.943265
Post-3 months (%)	12 (17)	47 (66.2)	5 (7)	7 (9.8)	0	

The *p*-value for the comparison between frame and mask fixation methods is *p*=0.943265, indicating no significant difference.

Mask fixation includes a mask over the temporal and parietal bones, areas of the skull where it is comparatively thinner from the frontal bone. The mask needs to fit tightly so as to reduce movement; however, its native flexibility within the skull does allow a little shift in it during treatment. This may be particularly problematic since the trigeminal nerve is very close to the temporal lobe and middle cranial fossa.[10] Unlike rigid fixation by the frame, the mask uses the tension of soft tissue to maintain the head position. Variability in patients' anatomy concerning the thickness and elasticity of soft tissue may influence the stability of mask fixation. Greater laxity in the skin and subcutaneous tissue may, for example, result in larger amplitude movements in some patients, which may threaten the precision of radiosurgery.[10]

Additional quality assurance (QA) procedures concerning targeting stability are included in the mask-based GKRS due to the flexibility inherent in mask fixation. These include frequent intra-procedural imaging with cone beam CT to verify alignment and correct for any shift. In contrast, the frame-based fixation employs rigid immobilization, which is screw-secured and, because of its inherent stability, requires less frequent checks in system alignment. Both maintain submillimeter accuracy; the mask-based approach simply entails enhanced QA protocols to maintain targeting accuracy.

Foramen Ovale and Foramen Rotundum are the transmission sites of the mandibular (V3) and maxillary (V2) branches of the trigeminal nerve, respectively. Because these structures lie close to the skull base and are encircled by other critical neurovascular structures, including the internal carotid artery and cavernous sinus, precise targeting is necessary to approach these structures closely. Misalignment during mask fixation might cause lethal radiation exposure to these regions.[4] This part of the petrous temporal bone, through which the trigeminal nerve passes before its entrance into Meckel's cave, is an important area that needs to be considered during treatment with the GK. Due to the complex anatomy in this region, proximity to the cochlea, and the internal auditory canal, precise targeting is necessary to avoid any injury to the auditory structure. In this, the rigidity of frame fixation is often preferred, but with appropriate implementation, advanced imaging in mask fixation can achieve similar precision.[9]

Because the trigeminal nerve is very close to the brainstem, even slight misalignment in targeting may result in a segment of the pons or medulla receiving radiation that can subsequently lead to serious neurological deficiency. Fixation by frame minimizes this risk since there is less head movement, whereas mask fixation would require the utmost care in verification by imaging to avoid this complication altogether.[13]

As shown in the research by Chen *et al.*,[4], several investigations demonstrate that the two modalities are equally accurate. Verified to be on par with frame-based approaches even with modest collimator sizes, the precision of the Novalis linear accelerator (LINAC)-based mask-based radiosurgery equipment is remarkable (<5 mm).[13,17] Gevaert *et al.*[8] agreed with our study when they evaluated the Novalis ExacTrac image guiding system's (Brainlab) detection and location accuracy to compare mask-based and frame-based radiosurgery techniques. They performed several radiosurgery placement methods (invasive ring, frame-based with relocatable mask, and frameless) and conducted a battery of concealed target tests. The 3D accuracy for the frameless, relocatable, and frame-based techniques was 0.76 ± 0.46 mm, 0.87 ± 0.44 mm, and 1.19 ± 0.45 mm, respectively. They found that the frame is more accurate than the mask but without significant differences.

For high-dose TN treatments, frameless stereoscopic radiographic imaging must have a targeting accuracy of 0.5–1 mm at any couch angle, as shown by Chen *et al.* (2010)[5] and Huang *et al.* (2018).[9] The geometric accuracy of the GK devices and the Novalis LINAC-based system are shown to be equivalent. There was no statistically significant difference in pain reduction between the groups when Chen *et al.* 2015[4] compared the results following TN stereotactic radiosurgery (SRS) with rigid head frame immobilization versus face mask immobilization.

Romanelli *et al.*[14] discovered that, compared to frame-based approaches, mask-based SRS had a rate of adequate pain management (BNI I-III) ranging from 60% to >80% 1 year following SRS. Kienzler *et al.* research[10] showed that compared to the 4-mm mask group, the 5-mm frame group had more effective long-term pain relief with fewer recurrences. Since the alignment accuracy of frame-based and mask-based approaches is comparable, they conclude that using a 5-mm collimator instead of a 4-mm one is responsible for this effect.

Limitations

The radiobiological response to the radiation dose and toxicity after the treatment were not assessed.

CONCLUSION

Our findings confirm that mask-based fixation in GKRS provides accuracy equivalent to traditional frame-based methods for treating TN while offering reduced pain and greater patient comfort. Enhanced quality assurance protocols – including precise calibration of the CBCT system, regular phantom testing, and integration of CBCT with MRI – ensure sub-millimeter targeting accuracy and consistent treatment delivery. Continuous imaging during the procedure allows for immediate correction of any patient movement, further enhancing precision. Consequently, mask-based fixation emerges as a reliable, noninvasive alternative that meets the stringent precision standards of frame-based methods in the effective management of TN.

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Ethical approval

IRB approval was waived by the ethics committee.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent.

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Conflicts of interest

There are no conflicts of interest.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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