Polish Journal of Medical Physics and Engineering
The Journal of Polish Society of Medical Physics
ISSN 1898-0309, doi: 10.2478/pjmpe-2025-0009

March 2025
Vol 31, Issue 1

Short Communication

The custom algorithm for the noninvasive CyberKnife system, designed to monitor eye position during radiotherapy

Agnieszka SKROBAŁA [1,2,ABCDEF,*], Szymon ŁUCZKO [3,ABCDEF], Józef GINTER [3,ABCDEF], Krzysztof MATUSZEWSKI [2,BDEF]

[1]*Department of Electroradiology, Poznan University of Medical Science, Poznan, Poland*
[2]*Department of Medical Physics, Greater Poland Cancer Centre, Poznan, Poland*
[3]*Department of Biomedical Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[*]*Corresponding author: Agnieszka Skrobała; agnieszka.skrobala@wco.pl*

(received 26 January 2025; accepted 3 March 2025)

Abstract

Introduction: Radiotherapy using the CyberKnife (CK) system for treating eye tumors requires tracking skull movements and immobilizing the eye. This study aims to develop a custom algorithm for a noninvasive eye position monitoring system in the CK framework.

Material and Methods: Retrospective data were analyzed from 13 patients treated with CK over five fractions. Eye immobilization was achieved using two guides above the patient's head, with a black dot as the fixation eye. Camera recording was used to analyze pupil movements. A Python-based algorithm was developed to calculate eye position angles relative to the desired direction. A Quality Index (QI) was defined as the Common Area (CA) ratio of the 80% isodose and Planning Target Area (PTA) to the isodose area shifted by eye movement. For simplicity, only horizontal eye movement (angle φ) was considered. Dose distribution and CT data were processed in ImageJ, and a script calculated CA values for all integer φ angles. MediaPipe was used to map facial landmarks, estimate iris contours, and track pupil center positions on the XY plane.

Results: The algorithm analyzed camera recording during fractions of radiation, issuing visual and auditory warnings when gaze angles exceeded 20°. Instantaneous and average QI values were also monitored, with violations prompting controlled therapy interruptions. Analysis of 7 patients showed effective eye tracking. Two patients struggled to maintain their gaze, leading to frequent warnings. For six recordings, issues arose due to missing facial landmarks, 90° image rotations, or partially closed eyes.

Conclusion: The custom algorithm provides real-time eye movement analysis and can enhance treatment quality monitoring in CK-based eye tumor therapy.

Keywords: stereotactic radiotherapy; eye tumor; movement tracking; CyberKnife.

Introduction

The most common type of primary eye tumor is uveal melanoma in the adult population.[1] Nowadays, stereotactic radiotherapy is an effective tool for treating ocular tumors.

The oldest type of treatment was enucleation, which involved completely removing the affected eye; however, this approach does not provide an advantage over eye-conserving therapy regarding metastatic spread or survival. Nowadays, external radiotherapy offers important treatment options for eye-sparing treatments like episcleral plaque brachytherapy and proton or hadron beam therapy[2,3] to stereotactic irradiation using the GammaKnife[4]. The primary drawback of GammaKnife-based techniques is the restricted number of treatment sessions due to the invasive immobilization method involving a skull-fixed head frame. Therefore, stereotactic radiotherapy (SRT) using the CyberKnife (CK) system for the treatment of uveal melanoma and other ocular tumors has proven to be an effective alternative way of treatment.[5] Stereotactic radiotherapy offers the best chance of preserving vision in the affected eye; however, some patients eventually require surgery. The tumor's size and location influence the likelihood of maintaining vision and preserving the eye with either technique. The dose delivered to the lens and optical disc is primarily determined by where the tumor is situated. Today, with the advent of frameless robotic radiosurgery technology, a treatment modality that does not require frame application can be applied. However, in CyberKnife radiotherapy, eye fixation is crucial in ensuring

© 2025 Authors
This is an open access article licensed under the Creative Commons Attribution-NonCommercial-NoDerivs License (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Authors' contribution:
A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

precise treatment delivery while tracking skull movement, which is essential for targeting tumors in the eye, such as ocular tumors. This study aims to develop a custom algorithm integral to a noninvasive eye position monitoring system within the CyberKnife framework.

Material and Methods

Treatment plans

The cohort for this study consisted of 13 patients treated with the CyberKnife system in 5 fractions for PTV = GTV + 2 mm, with a prescribed dose of 50 Gy at the 80% isodose line. The GTV was contoured as the ocular tumors on fused CT and MRI images with contrast. Ocular lesion treatment plans were prepared using the Precision ver. 3.3.1.3 treatment planning system (Accuray, Sunnyvale, California, USA) with fixed collimators. Beam formation was carried out using fixed collimators with 5 mm, 7.5 mm, and 10 mm diameters. The average treatment time was 20 to 30 minutes, depending on the GTV localization near organs at risk and the size of the PTV. **Figure 1.A** presents a typical example of dose distribution for an eye tumor in the CK-based system. Patient CT data (CT DICOM), along with data from the treatment planning system, including dose distribution (RT dose) and structure contours (RT structure), were used to create a custom algorithm integral to a noninvasive eye position monitoring system. The immobilization system was outlined as a structure to prevent beams from passing through it. A sample 3D visualization of the immobilization system and the beam configuration in the CK treatment planning system is shown in **Figure 1.B**.

Noninvasive eye position monitoring system

We developed a noninvasive eye fixation monitoring system to immobilize the affected eye and keep the patient's gaze direction fixed while acquiring CT images and CyberKnife treatment. The eye position system was used for the healthy eye when the patient could not see with the affected eye in order to control the gaze direction.

Figure 1.C illustrates the mask system that immobilizes the patient's head, and **Figure 1.D** the eye immobilization setup. This setup consists of two guides – one vertical and the other horizontal – placed at an angle above the patient's head. The guides are arranged to direct the patient's gaze toward a black dot on a disk at the end of the horizontal guide. An 8 mm diameter endoscopic camera represents the black dot. The settings of the two guides, which allowed for individual adjustments, were tailored to each patient's specific condition to ensure they could comfortably focus on the dot.

Patient's quality index

A custom algorithm supporting eye position control was developed in Python (Python Software Foundation, USA) based on the RT dose file and camera recordings from eye monitoring. This algorithm calculates the angle of the eye's gaze relative to the desired direction. Subsequent steps, including the custom algorithm and the programs or libraries used for their implementation, are collectively presented in **Figure 2**.

The common areas (CA) defined for the 80% isodose before and after eye movement, used to calculate a patient's quality index (QI), were determined using a macro script in ImageJ (National Institutes of Health, USA).[6]

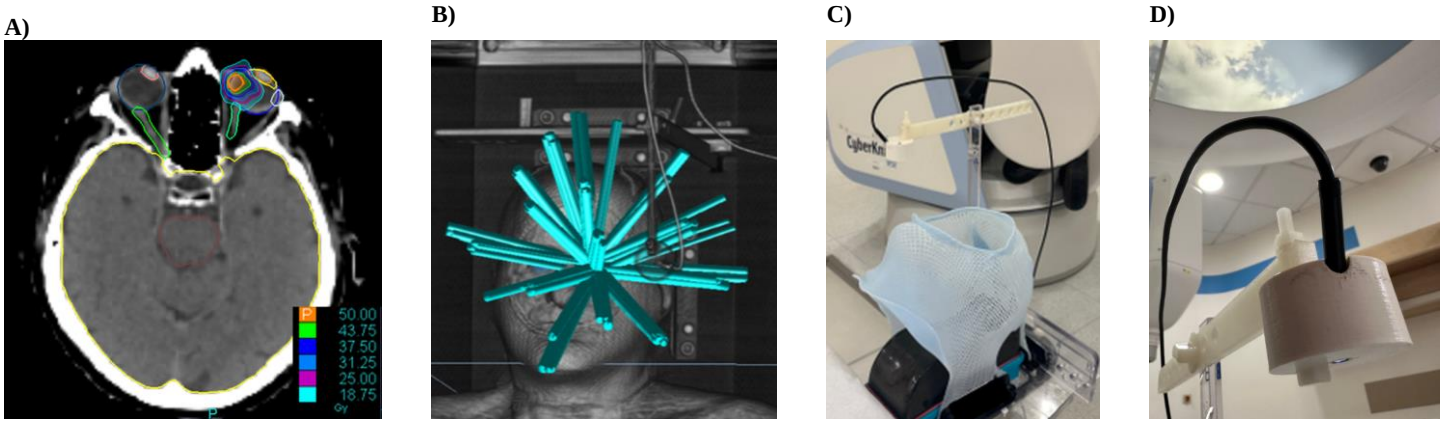


Figure 1. A) An example of dose distribution for an eye tumor, with the orange color representing the 80% isodose of 50 Gy. B) A 3D visualization of the immobilization system and the beam configuration in the CK treatment planning system. C) The head immobilization mask and an eye immobilization system consisting of two vertical guides and one horizontal guide placed at an angle above the patient's head, directing their gaze towards a black dot on a disk at the end of the horizontal guide. D) An 8 mm diameter endoscopic camera represents the black dot.

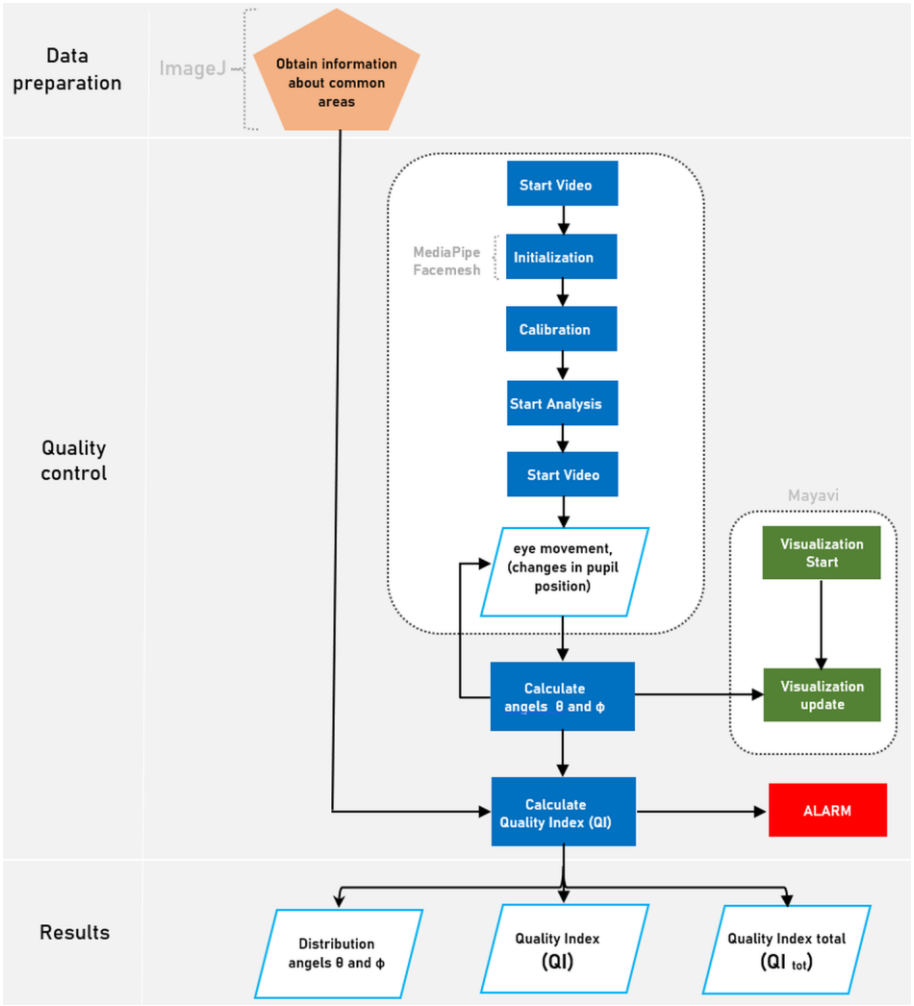


Figure 2. A diagram showing the subsequent steps includes a custom algorithm integral to a noninvasive eye position monitoring, enabling real-time quality control of radiotherapy.

For the custom algorithm, the Quality Index (QI) is defined as the ratio of the common area (CA) of the 80% isodose and the Planning Treatment Area (PTA), which rotates due to the eye's movement for different eye rotation angles (assuming the eye rotates as a rigid body) (**Equation 1**).

Only eye movement in the horizontal direction (left-right, angle φ) was considered to simplify calculations. Before an eye movement, the PTA and the 80% isodose almost overlap, ensuring the therapeutic dose delivery to the PTV. The isodoses and the associated surfaces defined by them are included in the RT dose for each patient. A simplified diagram showing the eye's horizontal movement, with the marked 80% isodose (yellow line), PTA (red line), and CA, is presented in **Figure 3.A**.

The total Quality Index of radiotherapy (QI_{tot}) was defined as the average QI from the start of irradiation to the present moment (**Equation 2**), where n represents the number of time points (the number of frames in the recording).

$$QI = \frac{CA}{PTA} \quad \text{Eq. 1}$$

$$QI_{tot} = \frac{1}{n}\sum_{i=0}^{n}\frac{CA_i}{PTA} \quad \text{Eq. 2}$$

where:
CA – Common Area: the area of the planned 80% isodose,
PTA – Planning Treatment Area,
and the PTA rotated by the movement of the eyeball.

To determine the value of the QI (**Equation 1**), a dataset containing the CA values for different eye rotation angles is required. Calculations were limited to horizontal eye movement direction (left-right, angle φ) for simplicity. The patient's dose distribution and the CT scan were loaded into ImageJ for this purpose. After marking the 80% isodose surface, a script was written to calculate the CA for all possible total rotation angles (φ) of the image relative to the center of the eye. The obtained data was imported into the program to estimate the QI for any patient based on their eye movements. Using the MediaPipe library (Google, USA), the program generates a grid of facial landmarks (**Figure 3.B**). Based on this grid, it calculates the coordinates of four points describing the iris of the observed eye, then outlines it and estimates the position of the pupil center on the XY plane, which aligns with the image plane.

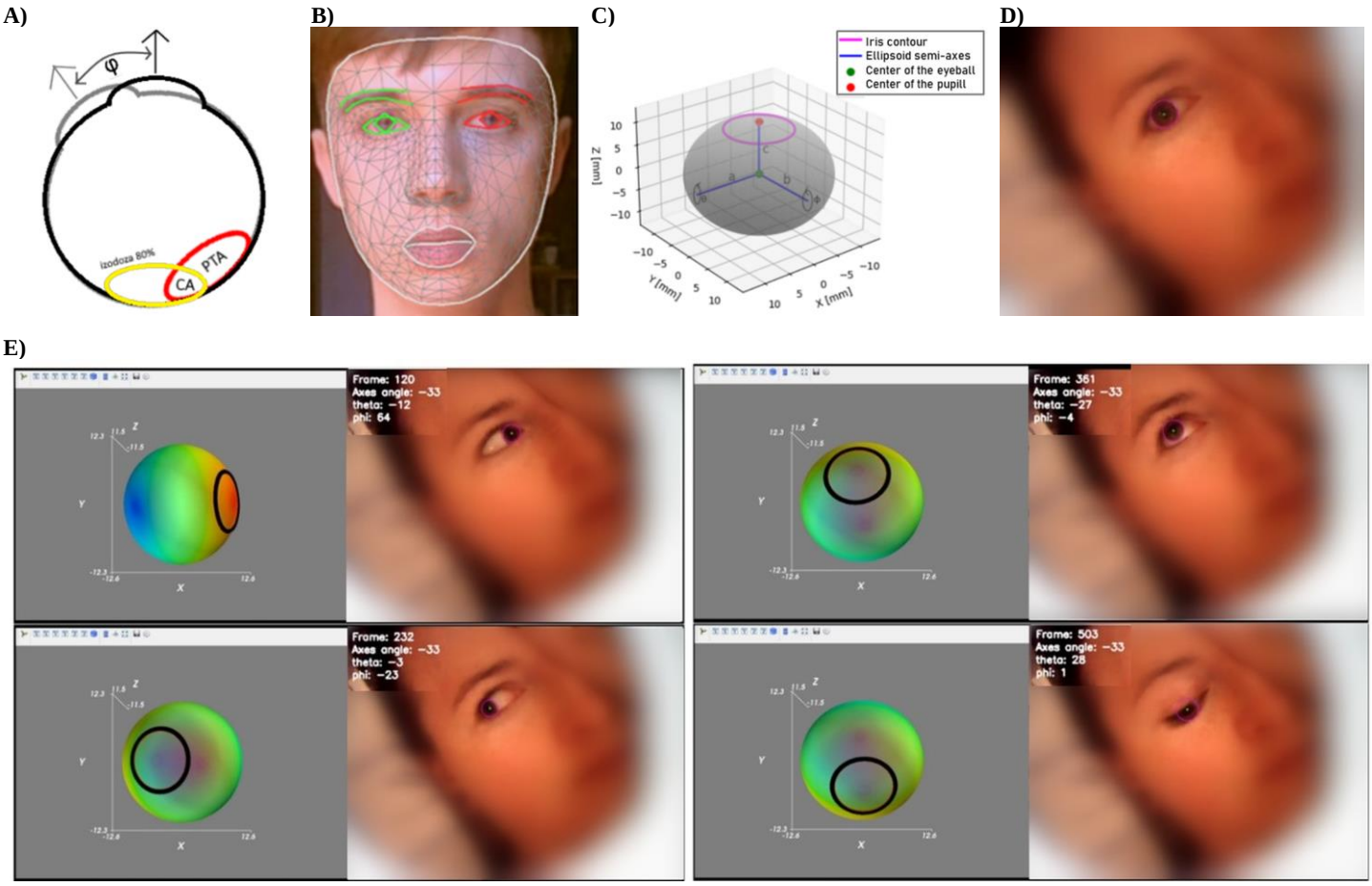


Figure 3. A) A simplified diagram showing the Planning Treatment Area (PTA) and Common Area (CA) surfaces on a horizontal cross-section of the eyeball. The black and yellow lines represent the eyeball in its initial position, along with the marked isodose defining the PTA surface. The gray and red lines represent the eyeball after rotating to the left, along with the marked shifted isodose. B) An example image of a face with an overlaid 'landmarks' grid. C) Visualization of elements for determining eyeball dimensions (iris contour in pink, approximated as an ellipsoid with semi-axes a, b, c in blue) and estimating eye movements and rotation angles. D) Sample image from the camera: pink color – iris, green color – the center of the pupil. E) Visualization in the program of the position of the eyeball based on the camera image, with the virtual eyeball undergoing the corresponding rotation.

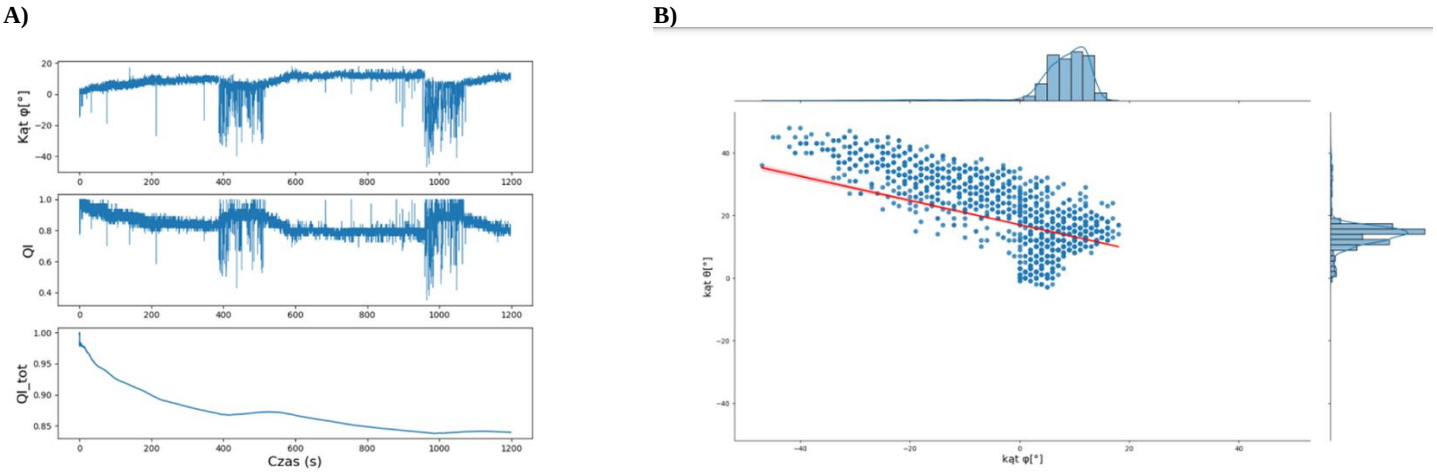


Figure 4. A) Graphs showing the changes in angle φ and the corresponding QI and QI_{tot} calculated based on it during ongoing radiation therapy for a selected patient. B) Graphs showing the correlation between angles θ and φ, along with the corresponding regression curve and histograms for a selected patient.

Calculating angles φ and θ

The program requires the patient to fix their gaze on the camera (the gaze fixation point) for calibration.

The dimensions of the eyeball approximated as an ellipsoid, were determined in millimeters using a CT image. The iris contour is represented in a pink line, and the semi-axis dimensions (variables a, b, c) are indicated by blue lines (**Figure 3.C**). These measurements also allow for estimating rotation angles (left-right, angle φ, and up-down angle θ). Assuming the head remains stationary and knowing the eyeball's dimensions (variables a, b, c) based on the ellipsoid equation, the program calculates the eyeball's rotation angles (left-right, angle φ and up-down angle θ). A sample image from the camera shows the iris in a pink line and the center of the pupil in a green point (**Figure 3.D**).

Results

A noninvasive eye position monitoring system during radiotherapy

The algorithm was implemented in a program designed to analyze the camera recording during each irradiation fraction. The program issues visual and audible warnings if the patient's gaze direction angle exceeds the predefined threshold (default: 20 degrees). Additionally, the program monitors the instantaneous and total quality index (calculated from the start of fraction radiation). If this parameter exceeds the set threshold, an alert is triggered to indicate the need for a controlled interruption of radiotherapy (**Figure 2**).

Visualization of the algorithm's functioning

The program enables the simultaneous verification of the calculated angles (φ and θ) by generating a real-time visualization of the examined eyeball's movements using the Mayavi library (Enthought, USA). During initialization, the user inputs the eyeball dimensions (semi-axes a, b, c) according to the patient's CT image, based on which a virtual eyeball is created. If the eyeball's position changes, as captured by the camera, the virtual eyeball undergoes the corresponding rotation in real time. This ensures accurate tracking of any positional changes (**Figure 3.E**).

Outcomes for patient

The analysis results for seven patients indicate that the program efficiently assessed pupil position. However, changelessness was observed in 2 patients who experienced significant difficulty maintaining a fixed gaze angle, which resulted in repeating visual and audible warnings. Issues with identifying the patient's gaze angle were noted in six recordings. These problems were attributed to avoidable factors, such as the absence of characteristic facial landmarks in the image (e.g., parts of the nose), a 90-degree image rotation relative to the horizontal plane, or a partially closed eye in two recordings.

The program also included a feature designed to detect potential head displacement, though no such alerts occurred during the analysis. An additional analysis using a virtual head phantom image estimated the error in gaze angle assessment (under ideal conditions with the head immobilized and the eye fully open) to be no greater than 2 degrees.

Real-time radiation therapy quality analysis for the patient

Change in the angle φ and the corresponding QI and QI_{tot} calculated based on it during ongoing radiation therapy for the patient (**Figure 4.A**). Significant periods of increased eyeball mobility during therapy were likely due to the patient's threshold for maintaining fixation, the exchange of the collimator, and the planned rest time. **Figure 4.B** presents graphs describing the involuntary movements of the treated eyeball during therapy, along with the overlaid linear regression curve. The regression curve indicates a negative correlation between these angles, which most likely related to slight changes in head position during therapy sections.The data shows that the patients made slight eye movements with standard deviations of 6.42°, 7.79°, and 11.71° for angle φ and 5.52°, 7.83°, and 7.99° for angle θ (**Table 1**), as recorded for three example patients.

Table 1. Mean and standard deviation (SD) of the φ and θ angle values for three example patients.

Patient	Angle φ		Angle θ	
	Mean	SD	Mean	SD
1	7.72°	6.42°	13.99°	5.52°
2	-0.16°	7.79°	15.06°	7.83°
3	0.04°	11.71°	13.41°	7.99°

Discussion

The custom algorithm analyzes real-time eye movement, enhancing treatment quality monitoring in CK-based eye tumor therapy. It estimates threshold values for angles θ and φ, as well as QI and QI_{tot}. When these thresholds are reached, the program can automatically interrupt radiotherapy to minimize side effects or prompt the patient to refocus on the fixation point. However, the algorithm has limitations, including errors in converting distance units from pixels to millimeters based on the assumed iris diameter, manual estimation of the common surface using ImageJ, and manual alignment of the face axis during calibration. Assumptions of complete head immobility and precise gaze at the camera center also affect the results. The Mediapipe library, used to determine pupil center coordinates, was developed with machine-learning techniques for well-visible human faces. However, hospital conditions did not always allow for optimal camera visibility. Despite these

limitations, the algorithm remains useful, allowing continuous verification through pupil position outlining and eyeball movement visualization.

In our custom program, we encountered similar challenges, which were addressed by other authors working on eye treatment using CK.[7] The treatment duration in CK radiotherapy, typically around 30 minutes, makes it difficult for patients to maintain a constant fixation point. However, like in standard CK therapy, the fixation point is a black dot displayed on the camera placed at the center of the pupil, requiring the patient to look straight ahead. This should theoretically make it easier to maintain gaze for the required duration. Accurately determining measurement errors remains challenging, as objective angle values during therapy are unavailable.

Our system integrates the radiotherapy process like the referenced study.[7] The study demonstrated the feasibility of a novel optical fixation system for linear accelerator-based stereotactic radiotherapy, featuring artifact-free camera application and automated eye movement monitoring with submillimeter precision. This resulted in significant improvements over existing methods. With well-defined interruption criteria and accelerated image processing, the system shows high potential for enabling automated, manually gated treatment beam delivery.

Other noninvasive ocular fixation techniques have also been described in the literature. Kheir WJ et al.[9] developed a stereotactic ocular localization box that can be securely attached and indexed to a stereotactic LINAC tabletop. This system incorporates adjustable LED lights as a fixation target and a CCD camera to monitor the patient's eye position. Other noninvasive ocular fixation solutions have also been explored in the literature. Iskanderani et al.[10] presented a method using a customized head frame and vacuum pillow system, effectively minimizing patient movement and improving treatment consistency and patient comfort without requiring invasive techniques.

Conclusions

The developed algorithm enables real-time images from a camera and serves as a valuable tool for assessing treatment quality for patients with ocular tumors treated using the CyberKnife system. The program enables additional verification of the calculated angles (left-right, angle φ, and up-down angle θ) by generating visualizations of the examined eyeball's movements in real time using the Mayavi library. At its current stage of development, the program has certain limitations. One of the main challenges is meeting specific conditions, such as proper camera positioning, which is generally achievable. However, the requirement for the patient to keep their eye sufficiently open to expose the pupil may be difficult for some patients to fulfill. Future development could address these limitations by incorporating 3D images of a patient's face during radiotherapy. This enhancement would allow for objective quantification of measurement errors, improving accuracy and reliability in treatment monitoring.

Acknowledgments

I would like to express my deepest gratitude to all those who contributed to the completion of this research, especially the radiation physicians from the Department of Radiotherapy III, the medical physicists from the Department of Medical Physics, and the radiation therapy technologists operating the CyberKnife system from the Department of Radiotherapy I.

Data availability statement

We provide a downloadable program on GitHub "Build Software Better, Together", https://github.com, gaze_analysis, designed to monitor eye position during radiotherapy. The software includes a detailed user manual and a technical report describing its functionality and implementation. To access the program, please email Józef Ginter at js.ginter2@uw.edu.pl.

Editor's comment

The abstract of the work was submitted to the 18th Congress of the Polish Society of Medical Physics (held in Poznań, Poland, 19-21 September 2024). The authors of the work were invited by the Scientific Committee of the Congress and the Editor-in-Chief of the Polish Journal of Medical Physics and Engineering to present their work in the form of a Short Communication in the Journal.

References

1. Spagnolo F, Caltabiano G, Queirolo P. Uveal melanoma. Cancer Treat Rev. 2012;38(5):549-553. https://doi.org/10.1016/j.ctrv.2012.01.002
2. Kheir W. J, Stinnet S. S, Meltsner S, et al. Preliminary results of uveal melanoma treated with iodine-125 plaques: Analysis of disease control and visual outcomes with 63 Gy to the target volume. Advances in Radiation Oncology. 2022;7(2):100869. https://doi.org/10.1016/j.adro.2021.1008693
3. Caujolle J-P, Mammar H, Chamorey E, et alP. Proton beam radiotherapy for uveal melanomas at Nice teaching hospital: 16 years' experience. International Journal of Radiation Oncology, Biology, Physics. 2010;78(1):98-103. https://doi.org/10.1016/j.ijrobp.2009.07.1688

4. Zehetmayer M, Kitz K, Menapace R, et al. Local tumor control and morbidity after one to three fractions of stereotactic external beam irradiation for uveal melanoma. Radiother Oncol. 2000;55(2):135-144. https://doi.org/10.1016/s0167-8140(00)00164-x
5. Schmelter V, Schneider F, Guenther SR, et al. Local recurrence in choroidal melanomas following robotic-assisted radiosurgery (CyberKnife). Ocular Oncology and Pathology, 2022;8(4-6):221-229. https://doi.org/10.1159/000527915
6. Schneider CA, Rasband WS, Eliceiri KW. NIH Image to ImageJ: 25 years of image analysis. Nature Methods. 2012;9(7):671-675. https://doi.org/10.1038/nmeth.2089
7. Daftari IK, Petti PL, Larson DA, et al. A noninvasive eye fixation monitoring system for CyberKnife radiotherapy of choroidal and orbital tumors. Medical Physics. 2009;36(3):719-724. https://doi.org/10.1118/1.3070537
8. Bogner J, Petersch B, Georg D, et al. A noninvasive eye fixation and computer-aided eye monitoring system for linear accelerator-based stereotactic radiotherapy of uveal melanoma. International Journal of Radiation Oncology Biology Physics. 2003;56(4),1128-1136. https://doi.org/10.1016/s0360-3016(03)00280-3
9. Kheir WJ, Stinnett SS, Meltsner S, et al. Novel frameless LINAC radiosurgery solution for uveal melanoma. Frontiers in Oncology. 2024;14:1365197. https://doi.org/10.3389/fonc.2024.1365197
10. Iskanderani O, Béliveau-Nadeau D, Doucet R, et al. Reproducibility of a noninvasive system for eye positioning and monitoring in stereotactic radiotherapy of ocular melanoma. Technol Cancer Res Treat. 2017;16:352-356. https://doi.org/10.1177/1533034617690979