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End-to-end testing of a method to fuse fundoscopy and MR images for ocular proton therapy

Introduction

- MR-based planning of Ocular Proton Therapy (OPT) is promising, but **accurate delineation of the tumor base is difficult** because flat tumor extensions cannot be distinguished on MRI.
- Fusing fundoscopy images with MR imaging can improve the accuracy of tumor base delineations. This requires a **patient-specific mapping** between the fundoscopy and MR image, to correct for **optical and geometrical deformations in the fundoscopy image** [1].
- This study performs an **end-to-end validation** of a previously developed mapping method.

Fundus camera calibration

The relation between input eccentricity and fundus image location was determined using a phantom based on an f-θ lens **(Figure 1)**. For the Topcon TRC50-DX camera, we found a **linear relation** between input eccentricities and image locations with a slope of **45 px/deg** (R^2=1, **Figure 2**).

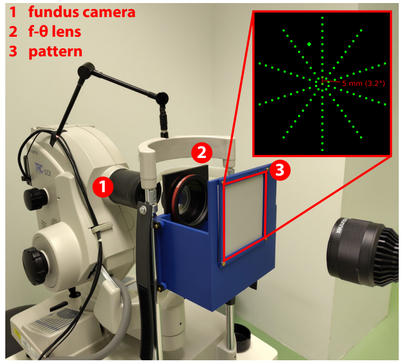


Figure 1: Camera calibration setup. Fundus photographs of a pattern of dots **(3)** are made through an f-θ lens **(2)**. Due to the f-θ lens, each dot location corresponds to a known eccentricity.

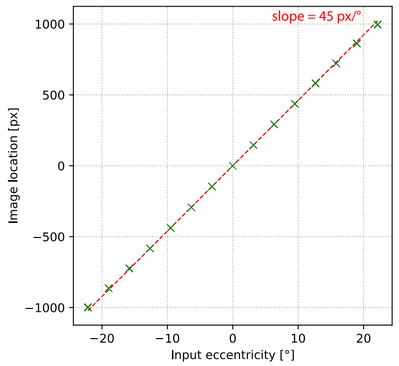
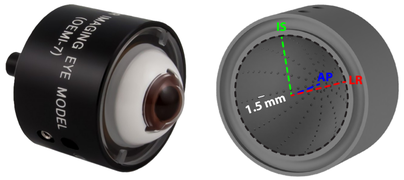


Figure 2: Measured image locations as a function of their eccentricity (crosses). The linear fit (dashed line) has a slope of 45 px/deg.



Phantom	R_{LR}	R_{IS}	R_{AP}	AL
Emmetropic	12	12	12	26
Myopic	12	12	18	28
Asymmetric	11	12	14	28

Figure 3: End-to-end validation phantom with three custom retinal cups. The retinal cups contain concentric rings of indented markers spaced 1.5 mm apart along the ellipsoid meridians. $R_{LR,IS,AP}$: retinal radii in the Left-Right, Superior-Inferior and Anterior-Posterior directions; AL: Axial Length.

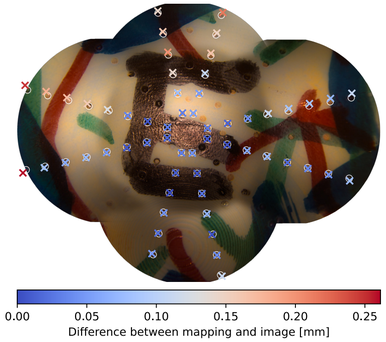


Figure 4: Fundus photograph of the emmetropic phantom with marker locations on the photograph (white circles) and predicted with the mapping method (crosses). Colors indicate the Euclidean distance between measured and predicted locations on the retina.

End-to-end validation

The existing OEMI-7 ocular phantom (Ocular Inc.) was used for an end-to-end validation of the method. Three custom retinal cups were designed with different refractive errors, resembling emmetropic, myopic and rotationally asymmetric eyes **(Figure 3)**. All phantoms contained concentric rings of indented markers at known locations. Dot locations were measured on fundus photographs of the phantom **(Figure 4)** and mapped to retinal locations using the previously developed method and camera calibration result. These locations were compared with the true marker locations. Differences between the true and mapped marker locations are shown in the table below and **Figure 5**. An example implementation in RayOcular on a μCT-scan of the phantom is shown in **Figure 6**.

Phantom	Eccentricity [°]	Difference [mm]
Emmetropic	37	0.10 ± 0.05
Myopic	32	0.28 ± 0.08
Asymmetric	37	0.29 ± 0.02

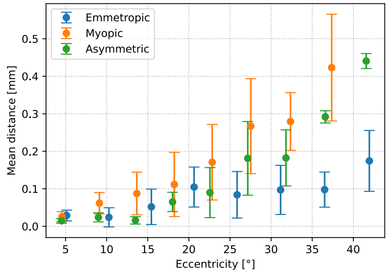
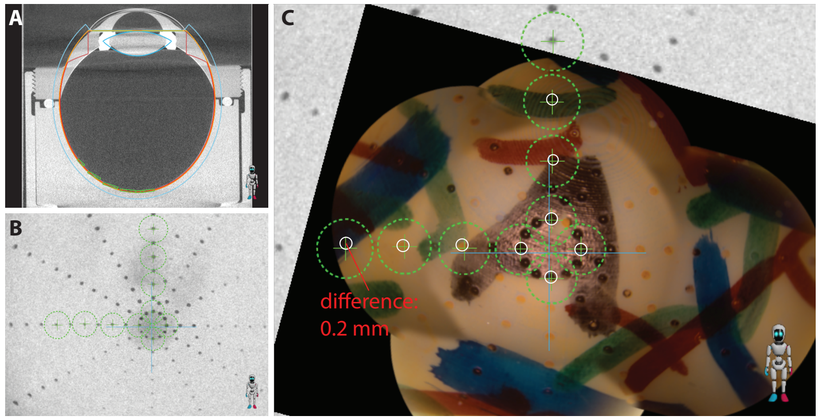


Figure 5: Euclidean distances between the true and mapped retinal locations of markers in the ocular phantom, as a function of the eccentricity. Error bars indicate the standard deviation.

Figure 6: Implementation of the mapping in RayOcular. **A)** Geometrical eye model superimposed on a CT-scan of the phantom. **B)** CT-based fundus view with annotated markers (green). **C)** Fundus view with overlaid fundus photograph. White circles indicate the marker locations on the photograph.



Limitations

- A slightly inaccurate **central scaling** can cause large peripheral differences.
- **Stitched fundus photographs** and **reprojections** applied during postprocessing can introduce additional errors [2].

Conclusion

Marker locations on fundus photographs are accurately mapped to retinal coordinates, with observed differences that are smaller than the uncertainty in tumor base delineations on MRI alone (0.62 mm) [3].

References
[1] Haasjes et al. (2025). Patient-specific mapping of fundus photographs to three-dimensional ocular imaging. *Med. Phys.* 10.1002/mp.17576
[2] Wulff et al. (2024). Uncertainties in ocular proton planning and their impact on required margins. *Phys. Med.* 10.1016/j.ejmp.2024.103358
[3] Jaarsma et al. (2023). Inter-Observer Variability in MR-Based Target Volume Delineation of Uveal Melanoma *Adv. Rad. Onc.* 10.1016/j.adro.2022.101149

Disclosures
The C.J. Gorter MRI Center receives research support from Philips Healthcare. The COMPOSE project receives research support from RaySearch Labs and is funded by NWO-VIDI, grant nr. 19704.

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