Magnetic resonance imaging analysis of anterior and posterior eye segment displacement during ocular gaze shifts

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PURPOSE. *To determine the relationship between movements of the posterior and anterior eye segments during arbitrary gaze shifts and to obtain information for monitoring fixation during radiotherapy for ocular diseases.*
METHODS. *We examined eye movements of ten emmetropic volunteers in a 1.5 T magnetic resonance system. Using a T2-weighted ultrafast turbo-spin echo sequence (UTSE), the eyes were examined within 21 seconds. Sagittal and transversal eye slices were obtained in five passages in five gaze directions (straight ahead, 15° above, 15° below, 15° right and 15° left of the primary position). Displacement of the posterior eye segment was analyzed in relation to the movement of the anterior segment in all directions.*
RESULTS. *The relationship between the movements of the anterior and posterior eye segment was 1:0.8 (± 0.06 SD) during horizontal gaze shifts and 1:1.16 (± 0.11 SD) during vertical gaze shifts.*
CONCLUSIONS. *Magnetic resonance imaging showed that the relationship between anterior and posterior eye segments was different during horizontal and vertical eye movements, indicating the presence of more than one center of rotation. Compared to the anterior eye segment, there was less displacement of the posterior eye segment during horizontal eye movements and more displacement during vertical eye movements. (Eur J Ophthalmol 2003; 13: 196-201)*

KEY WORDS. *MRI, Radiation therapy, Gaze shifts*

Accepted: July 1, 2002

INTRODUCTION

The relationship between movements of the anterior eye segment and the posterior eye segment is interesting from a scientific point of view and may also be of practical value in patients requiring radiation therapy for the retina. The relationship is dependent on the mechanics of ocular rotation. It has already been postulated that the center of rotation is not fixed, and non-rotational movement with rotation of the globe has been assumed for a long time (1-3). Berlin first described eye movements parallel to the axis of rotation as "screw movements" (4). Attempts to quantify these movements were first made by Fry and Hill (5). Progress in technology subsequently allowed two-dimensional video recording of the cornea, which revealed displacement of the center of rotation for saccadic eye movements as a function of fixation distance; however, simultaneous monitoring of the fundus was not done (6).

An optical method, the scanning laser ophthalmoscope (SLO), has now been used in attempts to establish the relationship between movements of the anterior eye and posterior eye segments by monitor-

1120-6721/196-6$03.00/0

ing movements of the cornea and retina (7). Because of optical distortion by the SLO, individual corrections are necessary (8, 9).

Magnetic resonance imaging (MRI) has no such optical pitfalls. Compared to computed tomography (CT), MRI gives sharper contrast of soft parts and has no radiation side effects, permitting examination of volunteers. MRI has been used to assess ocular motility, and for the measurement and functional observation of eye muscles (10-15).

The purpose of this study was to determine the relationship between movements of the anterior and posterior eye segments by MRI, with a view to using this information for monitoring fixation during radiotherapy for ocular diseases.

MATERIALS AND METHODS

We examined the eye movements of ten right emmetropic eyes of ten volunteers (five women, five men, mean age 32 years (26-43 years)) using a 1.5 T magnetic resonance system (ACS-NT Philips Medizinsysteme), in accordance with the following protocol: transversal and sagittal T2-weighted ultrafast turbo-spin echo sequences (UTSE) were obtained using a head coil. The volunteer's head was secured with a cast, so that the infraorbitomeatal line was perpendicular to the ground. A piece of cardboard with five fixation points drawn on it (straight, 4.5 cm (i.e., 15°) to the right, the left, above and below) was suspended between the head coil and the volunteer's head, centered in front of the right eye. To establish the distance between the cornea and fixation target a marker with high signal intensity on T2-weighted images was mounted on the back of the cardboard.

Dynamic sequences were obtained in five passages according to the five gaze directions (straight ahead, 15° left, 15° right, 15° up and 15° down). The scan time of each passage was 21 s using two signal averages in order to obtain an adequate signal-to-noise ratio. The acquisition matrix was 141 x 256 and the field size was set at 320 mm. Fifteen slices with a thickness of 3 mm and an intersectional gap of 0.3 mm were achieved in each passage. The repetition time (TR) was 1500 ms, the echo time (TE) 80 ms, and the turbo factor 21.

Using a rectangular field of view of 70%, we obtained a pixel (picture element) size of 1.3 x 1.6 mm, so we could identify eye movements of more than 1.5 mm. In MR imaging each pixel has a defined position in a 3 D coordinate system with its mid-point at the center of the MR scanner. Different locations of the nuclei in the scanner result in different phase dispersions and frequencies of the signal of the nuclei in the MR experiment. Differences in phase dispersions and frequencies determine the exact position of the nuclei in the coordinate system by Fourier transformation. The coordinates of each pixel can easily be identified on the MR scanner screen, and eye movements can

TABLE I - ORIGINAL MOVEMENT MEASUREMENTS OF THE ANTERIOR AND POSTERIOR EYE SEGMENT (in mm) DURING TRANSVERSAL AND SAGITTAL EYE MOVEMENTS

Volunteers	Transversal movements (15° left to 15° right)		Sagittal movements (15° up to 15° down)	
	Anterior segment	**Posterior segment**	**Anterior segment**	**Posterior segment**
1	5.4	4.4	4.7	5.5
2	6.0	4.6	4.9	6.8
3	6.0	4.3	4.3	5.6
4	6.1	4.8	4.8	5.3
5	6.1	4.6	4,9	5.6
6	5.8	4.6	5.0	6.3
7	6.7	4.7	4.9	6.0
8	5.5	4.1	5.6	6.1
9	6.2	4.5	6.6	6.5
10	7.8	4.7	5.0	5.4

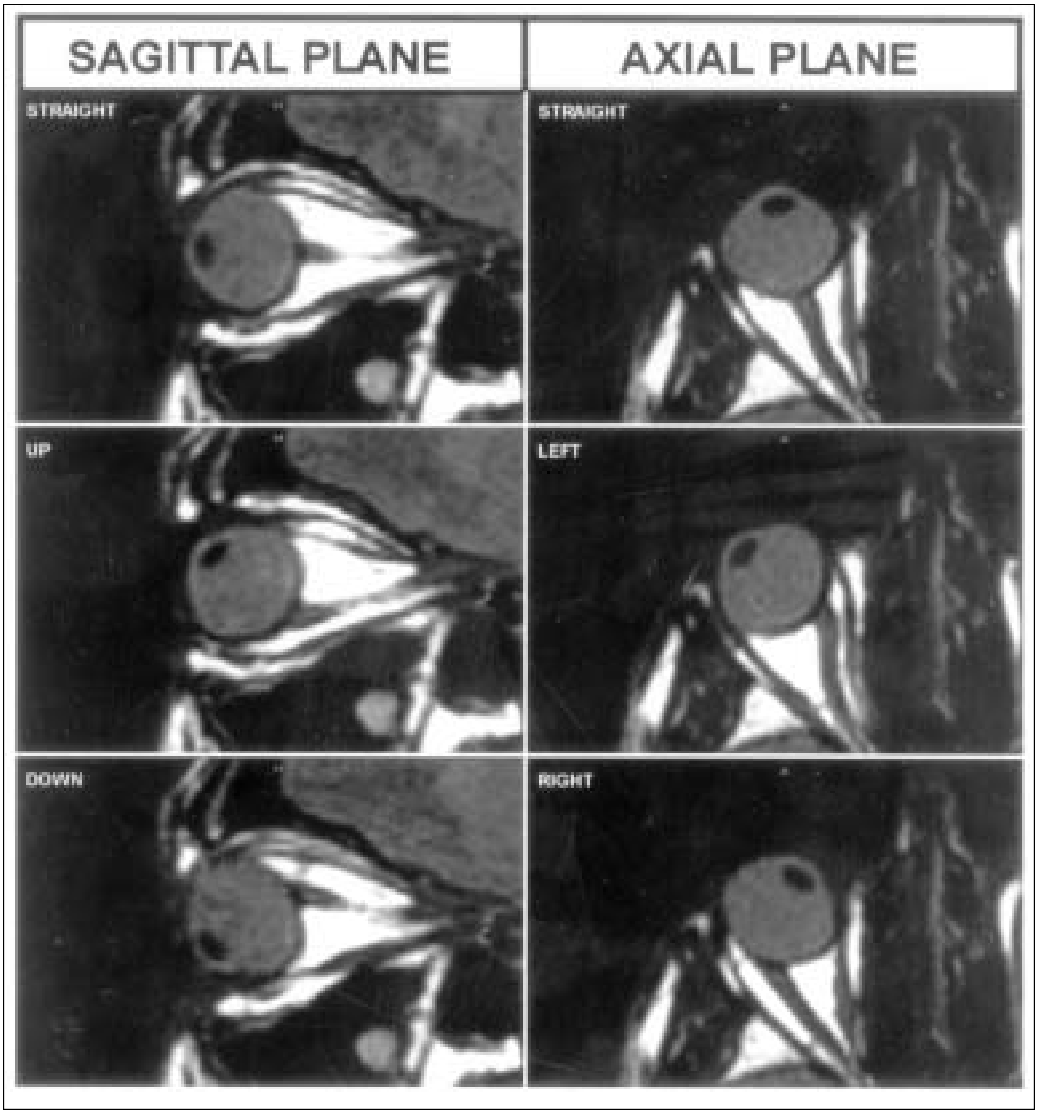

Fig. 1 - *Magnetic resonance images of one volunteer during gaze shift. Only representative images of the movements of the right eye at the level of the optic nerve are shown. The dynamic MR images are obtained according to the gaze directions indicated on the images. However, each picture element has a defined position in the 3 D coordinate system of the MR scanner. Consequently, movements of the anterior and posterior eye segments were determined by analyzing the coordinates of defined anatomical landmarks of the eye.*

be measured by analyzing the coordinates of certain set anatomical landmarks of the eye.

Since the cornea and retina are not visible with MRI, the axis of the eyeball was defined as the connecting line between the center of the lens and the center of the globe. Where this axis intersected the anterior contour of the lens and the posterior contour of the vitreous cavity was taken as the position of the anterior pole of the lens and the posterior pole of the retina. We measured any change in the direction of gaze and the resulting change in the position of the anterior pole of the lens in relation to the change in the position of the posterior pole of the retina. We analysed how movements of the anterior eye segment and posterior eye segment were related, using the software of the MR scanner.

The study was approved by the ethics committee of the University of Bonn and was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Volunteers gave their informed consent before admission.

RESULTS

The average mediolateral movement of the anterior eye segment, measured as the dislocation of the anterior pole of the lens, was 6.16 mm (± 0.68 mm

SD); the mean mediolateral movement of the posterior eye segment was 4.53 mm (± 0.21 mm SD). As regards craniocaudal movements, the mean anterior dislocation was 5.07 ± 0.63 mm, compared to 5.91 ± 0.51 mm for the retina. Table I shows the individual measurements. The ratio between the anterior and posterior eye segment as measured by MRI was 1:0.8 ±0.06 during mediolateral movements and 1:1.16 ± 0.11 during craniocaudal movements. An example of an individual MRI in different gaze shifts is given in Figure 1.

DISCUSSION

External beam radiotherapy is employed in the treatment of many ocular diseases. Age-related macular degeneration (AMD), a benign retinal lesion only a few millimeters in size, has lately been a focus for radiotherapy (16-19). There, field sizes of 1x1 cm up to 3x5 cm have been used (20-25). These are much larger than the affected retinal area. Such large fields are chosen to ensure that the macula remains within the treatment area despite possible eye movements. Preliminary studies have shown that patients do move their eyes during radiation, and the extent of these movements can be measured as corneal deviation by an observation camera. The mean corneal deviation was 1.0 ± 0.83 mm (range 0-6 mm) in the mediolateral direction and 0.7 ± 0.61 mm (range 0 - 4 mm) in the craniocaudal direction (7).

To reduce the radiation field it is important to know how movements of the anterior eye segment affect movements of the posterior pole. Based on the Gullstrand schematic eye, the center of rotation of the eyeball is estimated to be 13.5 mm behind the corneal apex and 1.6 mm to the nasal side of the geometric center of the globe. Using a cornea-fovea distance of 23.5 mm, the relationship between movements of the anterior and posterior eye segment would be 1.3:1. However, the Gullstrand eye does not qualify as a reliable basis for these evaluations, since there is more than one center of horizontal and vertical rotation within the eyeball (2, 26).

Scanning laser ophthalmoscopic examination of these eye movements shows different rotation attitudes in the mediolateral and craniocaudal directions: the ratio between movements of the anterior and posterior eye segment was 1:0.9 ± 0.1 (range 1:0.9 - 1:1.1) during horizontal eye movements and 1:1.5 ± 0.2 (range 1.3 - 1:1.9) during vertical eye movements (7). These results had already been corrected for optical distortion, as recommended by Ott and coworkers (8, 9). Since the optical difficulties could not explain the differences in the rotation pattern between mediolateral and craniocaudal movements, the idea of two different centers of rotation for craniocaudal and mediolateral movements was confirmed and quantified.

In the present study MRI was used as a non-optical system to evaluate the relationship objectively between movements of the anterior and posterior eye segment. With small discrepancies, the MRI values were consistent with the results found with the SLO. Movements of the posterior pole of the eye were greater than those of the anterior eye pole in the craniocaudal gaze direction.

MRI proved valuable in recording eye movements, but when analyzing the results one must take the following potential errors into consideration:

The axis of the eyeball was determined as the line connecting the center of the lens and the center of the globe. The intersection of this axis with the anterior contour of the lens and the posterior contour of the vitreous cavity defined the position of the anterior pole of the lens and the posterior pole of the retina. Compared to a round ball we assumed the globe to be approximately 10% deviated as an ellipsoidal spheroid (axis ratio 1.1:1.0) (Gullstrand standard eye). Taking this assumption into account, calculations showed that the length of unrollment and the position of the posterior pole have a maximum deviation of ± 3% (26).

As explained before, the center of rotation is not a single point. If, furthermore, we assume that owing to a misplacement of the volunteer's head/gaze, the center of gravity was not the center of rotation, but was shifted off the center of rotation by 10% (± 2mm) in any direction, calculations indicate that the length of unrollment and the position of the posterior pole have a maximum deviation of ± 2% (26).

We concluded that the shift of the posterior pole due to the eccentricity of the eye and the shift of the center of rotation were not significantly influenced. The position of the posterior pole within the retina was shifted less than ± 5% (<300 µm). Thus, the position of the posterior pole was located in a circular spherical area with a radius of 300 µm.

It can now be confirmed that during eye movement both rotation and translation of the eyeball occur within the orbit, as already assumed by Berlin and Frey and Hill (4, 5). In addition, we were able to quantify the relationship between rotational and translational movements in different gaze directions.

We can only speculate on the reason for the differences between horizontal and vertical eye movements. From the anatomical standpoint there are few restrictions in horizontal eye movements. However, vertical eye movements can be restricted by Whitnall's ligament above and Lockwood's ligament below the anterior part of the eye, so further movement can only be achieved by translation.

The small differences between the SLO and MRI results may partly be due to the different landmarks used for calculation: the corneal limbus and the macula were recorded by SLO, whereas the anterior pole of the lens and the posterior border of the vitreous cavity were used for MRI. The individual orbit anatomy may also have an impact.

In conclusion, our results indicate that MRI is a valuable method of depicting eye movements objectively. The findings confirmed previous results with the SLO.

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