Comparison between anisometropic and strabismic amblyopia using functional magnetic resonance imaging

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Abstract

Aims—To assess calcarine activation with functional magnetic resonance imaging (fMRI) in patients with anisometropic and strabismic amblyopia.

Methods—14 amblyopes (eight anisometropic and six strabismic) were studied with fMRI using stimuli of checkerboards of various checker sizes and temporal frequencies. While T2* weighted MRI were obtained every 3 seconds for 6 minutes, patients viewed the stimuli monocularly with either the amblyopic or sound eye. Results—Amblyopic eyes showed reduced calcarine activation compared with contralateral sound eyes in fMRI in all subjects. The calcarine activation from amblyopic eyes in anisometropic amblyopes was more suppressed at higher spatial frequencies, while that from amblyopic eyes in strabismic amblyopes was more suppressed at lower spatial frequencies. Conclusion—These results suggest that fMRI is a useful tool for the study of amblyopia in humans. The calcarine activation via amblyopic eyes because of anisometropia or strabismus has different temporospatial characteristics, which suggests differences in the neurophysiological mechanisms between two types of amblyopia.

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Amblyopia is defined as abnormally low visual acuity, even with optical refractive correction and in the absence of any obvious retinal or central pathology. Clinical experience indicates that amblyopia is caused by form vision deprivation and/or abnormal binocular interaction in early childhood. Amblyopia can be induced during a critical period in experimental animals by unilateral eyelid suturing, optically induced anisometropia, and surgically induced strabismus. The animal studies showed that the number of visual cortical neurons which can be activated by visual stimulation of the amblyopic eye were reduced, and that shrinkage of cells in layers of the lateral geniculate nucleus connected to the amblyopic eye had occurred. In an earlier study with human anisometropic and strabismic amblyopia, histological findings of the lateral geniculate nucleus were consistent with those in the animal studies. However, the normal finding of ocular dominance columns in the human cases of anisometropic amblyopia and accommodative esotropia was reported by Horton et al. These findings suggest that ocular dominance columns are probably no longer susceptible to shrinkage at the age after the critical period for amblyopia. Also, they speculated that milder forms of amblyopia may have a different cortical basis from amblyopia produced by early, severe form deprivation.

Recently, cortical activity in amblyopes has been studied with new techniques to understand the neurophysiological mechanism underlying amblyopia. Blood oxygenation level dependent functional magnetic resonance imaging (fMRI) utilises the focal uncoupling of cerebral blood flow and metabolism to detect focal brain activation. In the previous fMRI studies with normal subjects, visual stimulation produced an increase in the intensity of MRI signals in the primary visual cortex. In the case of amblyopes, there were fewer activated fMRI voxels during amblyopic stimulation than during normal eye stimulation. However, the functional imaging studies in human amblyopes have suggested that striate cortex activity levels remain unchanged, while others drew the opposite conclusion.

The purpose of the present study was to examine ocular findings and calcarine activation in the case of amblyopes, and to evaluate differences in the response patterns between anisometropic and strabismic amblyopes.

Subjects and methods

This study was performed in accordance with our institution's guidelines and the Declaration of Helsinki, and the protocols were approved by the institutional review board of the Seoul National University Hospital.

This study involved amblyopic subjects, having best corrected visual acuities in the sound eye of 6/6 or better, and 6/18 or less in the amblyopic eye, with no history of ophthalmological or systemic diseases. In the group of anisometropic amblyopias, patients with anisometropia, defined as a spherical difference between the two eyes of 3.0 dioptres or more, and with no heterotropia in the alternate cover test were included. Strabismic amblyopes had esotropia or exotropia of at least 15 prism dioptres in the alternate cover test and a spherical difference between the two eyes of less than 0.5 dioptre. All subjects gave written informed consent for the procedure after the purposes, risks, and benefits of this study were explained.

Subjects were positioned supine in the magnet, and silicone cups were placed over the ears.
to reduce the gradient noise. To minimise non-
visual cerebral activity, subjects were asked to
lie without any movement. During the study,
the subject viewed stimuli through prism
glasses on a screen positioned at the subject’s
feet. The visual stimuli were black and white
checkerboard patterns at spatial frequencies of
0.25, 0.5, 1, and 2 cycles/degree of visual angle
(that is, individual check sizes of 2, 1, 0.5, 0.25
degrees of visual angle, respectively). Each
subject received alternating stimuli at temporal
frequencies of 2, 4, 8, and 16 Hz. During
monocularly applied visual stimuli, fMRI scans
were set to use T2* weighted images at 1.5T
using a gradient echo EPI sequence (surface
coil on the occiput, TR 3 seconds, TE 60 ms,
FA 90, FOV 24 × 24 cm, matrix size of 128 ×
128, 15 slices 3 mm thick). The total time for
one fMRI experiment was 6.0 minutes. The
images were reconstructed off-line, exported to
volumes, and aligned for movement correction
using an AIR3.0 package. Gaussian filtering
was performed to enhance signal to noise ratio
for a biologically appropriate signal, other than
intrinsic filtering embedded during recon-
struction of MRI form K-space data.

During each trial, fMRI scan was also
performed on the sound eye during monocular
viewing with a plus lens to produce optical
defocus with the same level of visual acuity as
the amblyopic eye at a 6 metre viewing
distance. A checkerboard frequency of 8 Hz
was used as a visual stimulus, because this rate
had been previously found to maximise cere-
bral blood flow and minimise the scan time.

Sagittal slices from a conventional MRI were
used to identify the plane of the calcarine
fissure bilaterally. We derived the visually acti-
vated state after the region of interest was
determined around the calcarine sulcus ac-
line with the calcarine fissure bilaterally. We
derived the visually activated state after the re-

gion of interest was determined around the calc

Table 1  The ophthalmological findings of nine amblyopes

<table>
<thead>
<tr>
<th>No</th>
<th>Age</th>
<th>Sex</th>
<th>Strabismus</th>
<th>BCVA (Refractive error based on cycloplegic refraction)</th>
<th>Normal eyes</th>
<th>Amblyopic eyes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>M</td>
<td>Eso, 50</td>
<td>6/6 +0.50D = +0.50Dc A90</td>
<td>6/120 +0.50Dc = +0.50Dc A90</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>M</td>
<td>Eso, 16</td>
<td>6/6 +0.25D = +0.25Dc A90</td>
<td>6/30 +0.75D = +0.50Dc A90</td>
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</tr>
<tr>
<td>3</td>
<td>23</td>
<td>F</td>
<td>Eso, 35</td>
<td>6/6 +0.25D = +0.25Dc A90</td>
<td>6/60 +0.25D = +0.25Dc A90</td>
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</tr>
<tr>
<td>4</td>
<td>23</td>
<td>F</td>
<td>Eso, 25</td>
<td>6/6 +1.00D = +0.50Dc A180</td>
<td>6/45 +1.00D = +0.50Dc A180</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>F</td>
<td>Ortho</td>
<td>6/6 +0.50D = +0.50Dc A90</td>
<td>6/50 +0.25D = +0.75Dc A90</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>M</td>
<td>Ortho</td>
<td>6/6 +0.25D = +0.25Dc A90</td>
<td>6/30 +1.00D = +0.25Dc A90</td>
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</tr>
<tr>
<td>7</td>
<td>9</td>
<td>M</td>
<td>Ortho</td>
<td>6/6 +0.25D = +0.25Dc A90</td>
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<td>8</td>
<td>9</td>
<td>M</td>
<td>Ortho</td>
<td>6/6 +0.25D = +0.50Dc A90</td>
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<tr>
<td>9</td>
<td>15</td>
<td>F</td>
<td>Ortho</td>
<td>6/45 +1.50D = +1.00Dc A90</td>
<td>6/30 +4.50D = +0.50Dc A90</td>
<td></td>
</tr>
</tbody>
</table>

PD = prism dioptre, BCVA = best corrected visual acuity, Eso = esotropia, Eixo = exotropia, Ortho = orthotropia, Ds = spherical lens dioptre, Dc = cylinder lens dioptre

Results

Fourteen subjects ranged in age from 5 to 32
years. Eight had anisometropic amblyopia
(anisohypermetropic amblyopia in seven, ani-
omyopic amblyopia in one) and the range of
the differences in spherical equivalents of two
eyes was 3.5–8.3 dioptres. Six had strabismic
amblyopia (esotropia in four, exotropia in
two); the range of the deviation was 16–50
prism dioptres. No abnormalities in the ERG
of amblyopic eyes were found, and no differ-
ences in the ERG responses of the amblyopic
and sound eye were found in any subject.

We excluded five subjects who showed signifi-
cant movement artefacts in the fMRI results, in
spite of the attempt to correct for them. There-
fore, four anisometropic and five strabismic
amblyopes were analysed. Data collected during
the study, including visual acuity and refractive
status are summarised in Table 1.

The calcarine activation in amblyopic eyes,
whether due to anisometria or strabismus,
showed a reduced response compared with the
sound fellow eyes (Fig 1). There was statistical
significance at 0.25–1° in anisometropic am-
bylopes and at 0.5–2° in strabismic amblyopes.

Figure 1  Examples of calcarine activation are shown for an anisometropic patient (upper)
and a strabismic patient (lower), in which the activation by amblyopic eyes was found to be
significantly less than that for the sound eyes. Images are vertically aligned along the calcarine
fissures with occipital lobes. During visual stimulation, local increases in signal intensity were
detected in the medial-posterior regions of the occipital lobes along the calcarine fissures. Yellow
coloured regions represent a more activated state than the red coloured regions.
In amblyopes, optical blur of the sound eyes reduced calcarine activation, but there was no statistically significant difference induced by optical blur (p > 0.05, Fig 2, Table 2). The trend towards a reduction was seen in the variable temporal frequency, especially in anisometropic amblyopia, and this finding was statistically significant at 4 and 8 Hz (p < 0.05, Fig 2, Table 2).

**Table 2**  
*p* Value of percentage of functional MRI signal between amblyopic eye or defocused eye and sound eye in amblyopes

<table>
<thead>
<tr>
<th>Spatial frequency (cycles/degree)</th>
<th>0.25</th>
<th>0.5</th>
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<th>2</th>
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<tbody>
<tr>
<td>Anisometropic amblyopia</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Amb and sound</td>
<td>0.12</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
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<tr>
<td>Defocused and sound</td>
<td>0.37</td>
<td>0.43</td>
<td>0.07</td>
<td>0.45</td>
</tr>
<tr>
<td>Strabismic amblyopia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amb and sound</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.08</td>
</tr>
<tr>
<td>Defocused and sound</td>
<td>0.11</td>
<td>0.08</td>
<td>0.32</td>
<td>0.24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temporal frequency (Hz)</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anisometropic amblyopia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amb and sound</td>
<td>0.06</td>
<td>0.02</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>Strabismic amblyopia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amb and sound</td>
<td>0.17</td>
<td>0.24</td>
<td>0.24</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Amb and sound = *p* value between amblyopic eyes and sound eyes.

Defocused and sound = *p* value between sound eyes defocused with optical blur and sound eyes.

**Discussion**

Cortical activity in human amblyopia has recently been reported using new techniques. Demer et al employed positron emission tomography (PET) for amblyopic adults and control subjects. They found that activity in the primary visual cortex of amblyopes was 5–6% less during the stimulation of the amblyopic eye than during the stimulation of the sound eye. Kabasakal et al showed the visual cortex response of the amblyopic eye to light stimulation was severely reduced when compared with the sound eye, in an evaluation using brain single photon emission computed tomography. These results were verified by our study.

Our data demonstrate that the fMRI signal changes in the calcarine activation were, in general, smaller when viewed with amblyopic eyes than with sound eyes, in all amblyopes. These results probably reflect that amblyopia has an associated abnormality in or before the calcarine cortex. However, the lack of formed images on the retina of the amblyopic eye could lead to profound defects in calcarine activation. To exclude this possibility, we investigated the calcarine activation during viewing by an amblyopic eye that was simulated by...
optically blurring the sound eye to reduce visual acuity to a comparable level. Monocular stimulation of the sound eye showed a reduced calcarine activation during viewing with optic blur; however, there was no statistical significance whether the condition was blurred or not. This finding is different from the previous report that optic blur reduced activity in primary visual cortex by about 8% in control subjects. 14

In the previous study using PET, the cortical response evoked by the amblyopic eye was significantly reduced in the ipsilateral Brodmann areas 18, 19 with no significant change in the Brodmann area 17 in the cases of strabismic amblyopia. 12 These findings are different from those of the present study that anisometropic as well as strabismic amblyopes show a reduced fMRI response in calcarine cortex.

Reports of the effects of spatial frequency or temporal frequency on visual perception have been mixed. Cascairo et al reported that the contrast visual acuity in both anisometropic and strabismic amblyopes was reduced for the ambyopic eye at higher contrast levels. 26 On the other hand, others have demonstrated that strabismic amblyopes had abnormalities only at the higher spatial frequency, whereas anisometropic amblyopes were found to have an abnormal function in both the low and high spatial frequency ranges. 27-28 The present study evaluated calcarine activation according to variable frequency, showing statistical significance at 0.25–1° in anisometropic amblyopes and at 0.5–2° in strabismic amblyopes.

In terms of the temporal frequency, the regional cerebral blood flow response peaked at 7–8 Hz in normal subjects. 30 31 We observed a significant difference at 4 and 8 Hz in anisometropic amblyopes, while there was no significant difference at any level of temporal frequency in the calcarine activation of strabismic amblyopes. The reason for the discrepancy between the two types of amblyopes is unclear and requires further investigation focusing on the change in properties of visual stimuli.

Anderson et al reported that the extent of the deficit was not correlated with either Snellen acuity or contrast sensitivity by magnetoencephalography. 11 In contrast, functional activation of the calcarine cortex was reduced in amblyopic eyes compared with sound eyes to a degree more closely correlated with visual acuity than were visual evoked potential amplitude and at the higher spatial frequency, whereas anisometropic amblyopes were found to have an abnormal function in both the low and high spatial frequency ranges. 27-28 The present study evaluated calcarine activation according to variable frequency, showing statistical significance at 0.25–1° in anisometropic amblyopes and at 0.5–2° in strabismic amblyopes.

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