Neural contrast sensitivity measurements with a laser interference system for clinical and screening application

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A He-Ne laser interference device for clinical measurements of the neural contrast sensitivity function (CSF) is described. The system uses planoparallel glass plates for the generation of sinusoidal gratings on the retina. Incoherent light from two light-emitting diodes is superimposed for reducing the contrast to a range from $2 \times 10^{-3}$ to 0.5. The device is coupled with a microcomputer that calculates the contrast sensitivity (CS) and permits control of the system by a dialogue program. The mean CSF for normal observers (95 eyes) is presented, and the data are compared with overall CS values from other authors. Pathologic CSFs of three patients are shown as examples for the clinical application. For screening purposes the CS values for five spatial frequencies are compared with the normal CSF, and loss-of-contrast values are calculated. (INVEST OPHTHALMOL VIS SCI 21:737-744, 1981.)

Key words: laser interference, neural contrast sensitivity, psychophysical measurement, sinusoidal gratings

The contrast sensitivity function (CSF) for sinusoidal gratings is being tested for clinical application since it has proved its value for the theoretical understanding of spatial vision. Most of the authors presented the test patterns on a TV screen or oscilloscope, thus measuring the overall CSF, including the modulation transfer function of the eye. Only a few authors used the laser interference method introduced by Campbell and Green, which we think is the appropriate method for clinical conditions (where many patients show a degradation of the optical quality of the eye) but is a little difficult to use. In this paper we describe a very compact instrument attached to a slit lamp/ophthalmic microscope, which permits measurements of the neural CSF under routine conditions.

Method

We intended to make CSF measurements at 10 spatial frequencies in a foveal area of about 5 degrees in diameter, using a circular test field for avoiding different edge effects at the minimum or maximum of fringes. The surrounding field was dark. If one considers that at least five periods should be presented to avoid a threshold elevation for low frequencies, the lowest frequency is 1 cpd. The highest frequency was set to 45 cpd because finer gratings can be seen only by well trained observers. This frequency range was divided into 10 logarithmic equidistant steps.

As contrast range we found $2 \times 10^{-3}$ to 0.5 to be sufficient. Standard fringe orientation was vertical to allow comparisons with the results of other authors, but for CSF measurements at different meridians it should be possible to rotate the fringes.

Red He-Ne laser light was considered to give results comparable with measurements at other wavelengths. These authors have also shown that
region of interference from laser

Fig. 1. Generating laser interference fringes on the retina by splitting the laser beam at a planoparallel glass plate and focusing the reflected beams in the eye.

Fig. 2. Laser interference system for CS measurements—optical setup. \( P_1 \) to \( P_3 \), Sheet-type polarizers; \( BS_1 \) and \( BS_2 \), beam-splitting cubes.

A maximum luminance-independent contrast sensitivity (CS) requires a mean retinal illumination of at least 10\(^3\) trolands (corresponding to a luminance of 150 cd/m\(^2\)). We chose this luminance, which is also the lower limit for visual acuity measurements under photopic conditions. The fringes were presented without flicker to ensure that the perception of contrast and not of motion was tested.

The CSF measuring system was based on a device that generates sinusoidal gratings with light from a 1 mW He-Ne laser. This instrument\(^*\) was designed for the measurement of retinal visual acuity and provides 10 spatial frequencies from 1 to 33 cpd at high contrast by using planoparallel glass plates as beam splitters. The principle is shown in Fig. 1. The laser beam in Fig. 1, \( a \), is partially reflected at the front and rear surface of the glass plate with thickness \( d \).

The reflected parallel beams of separation, \( a \), are focused in the posterior nodal plane of the patient's eye (Fig. 1, b) and produce sinusoidal interference fringes, as described by Campbell and Green. The spatial frequency, \( f_s \), of the fringes for the laser wavelength \( \lambda \), is given by

\[
f_s = \frac{1}{\text{arcsin}\left(\sqrt{\frac{a}{d}}\right)}
\]

The separation, \( a \), is proportional to the thickness, \( d \), of the glass plates according to

\[
a = d/\sqrt{n^2 - 0.5}
\]

where \( n \) denotes the index of refraction of the glass plates. Thus \( f_s \) is given by

\[
f_s = \frac{1}{\text{arcsin}\left(\sqrt{\frac{n^2}{1.506^2} - 0.5/d}\right)}
\]

If the laser foci are imaged into the eye with a magnification factor \( m \), unequal to unity, \( d \) is replaced by \( d \cdot m \).

For the purpose of CSF measurements the glass plates of the Retinometer were replaced by others giving a spatial frequency range from 1 to 46 cpd with logarithmic equidistant steps. In Table I we give the dimensions of our glass plates for a magnification factor of 0.445 and an index of refraction of 1.506.

The contrast of the interference fringes was controlled by superimposing incoherent light from

\*The Rodenstock Retinometer (see Rassow and Wolf).
two light-emitting diodes (LEDs) (LED₁ and LED₂ in Fig. 2). The first LED gives a continuous contrast range from $4 \times 10^{-3}$ to 0.99. This is achieved in a common way by placing two sheet-type polarizers, P₁ and P₂, into the laser and LED beam with transmission axes perpendicular and controlling the intensities by rotating a third polarizer, P₃, behind the beam-splitting cube BS. The angle of rotation is $\theta$, with $\theta = 0$ for P₂ and P₃ parallel (minimum contrast). If the laser and the LED are color- and luminance-matched, the total luminance and color impression remain constant when P₃ is rotated, and the contrast varies with $\sin^2 \theta$. The second LED reduces contrast to a range from $2 \times 10^{-3}$ to 0.5.

For maintaining a sufficiently small image of the LEDs in the eye's pupil, we cut off the spherical part of LED₁ and polished the flat surface. We had then nearly a point source, the image of which had a diameter of 2 mm. This is small enough to allow for slight movements of the fixating eye.

The angle between the transmission axes of P₃ and P₂ is encoded by a 250-increment encoder attached to the gear. The angular resolution is 1 min arc. The position of the glass plate revolver is monitored by a binary coded decimal encoder, giving a digital representation of spatial frequency.

Fig. 3 shows a block diagram of the signal processing. The spatial frequency code is passed to I/O ports of a microcomputer, and the signals from the angular encoder are passed to a decimal up/down counter and to the I/O ports. The counter permits the operator to estimate the actual fringe contrast from the encoder reading. The patient's answer is processed with priority by interrupt. The whole assembly is shown in Fig. 4.

**Laser safety**

The main part of the laser light (about 80%) passes the glass plate beam splitters and is absorbed in the glass plate revolver (see Fig. 2). A neutral-density filter (not shown), polarizers, and two 1:1 beam-splitting cubes reduce laser power to $3 \times 10^{-8}$ W at the patient's cornea. With a theoretically minimum possible focus diameter of about 20 μm, this is a power density of $10^{-2}$ W/cm². Since the light is focused in the anterior part of the eye, considerable absorption takes place only in the iris, for which safety limits have not been established. But one can estimate damage threshold power densities from experiments with rabbits. Rassow and Dannheim found a limit for visible lesions of about 40 W/cm² at 460 to 514 nm (argon laser) for exposure times longer than 0.1 sec. Thus the power density for our CSF measurements is more than 3 decades below that lesion threshold. A comparison with the values given by the American National Standard Institute (ANSI Z 136.1, 1976) also shows that the output of the instrument is far below a dangerous level. The maximum permissible exposure for extended sources is 20 W/cm²·sterad. For a pupil plane of 0.5 cm² and the apparent visual angle of our source of 0.005 sterad, this gives a permissible energy of...
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Fig. 4. Assembly of the contrast sensitivity measuring system. 1, Laser interference system, mounted on ophthalmic microscope; 2, control unit; 3, teletype; 4, microcomputer; 5, operator’s place; 6, patient’s place.

Fig. 5. CSF for normal observers (95 eyes) from 12 to 71 years old, with five measurements at each spatial frequency. Hatched area, Mean values and 95% tolerance interval.

Results

Normal observers. For calibrating the method, the CSFs of normal observers 12 to 71 years old (95 eyes) were determined from five measurements at each spatial frequency.

Prior to each measurement the fringes of a certain spatial frequency were presented slightly above threshold contrast for drawing the subject’s attention to that frequency without elevating the threshold by adaptation to a high-contrast grating. Then the contrast was reduced to minimum and raised again with a speed of 0.2 log units/sec until the subject detected the fringes.

The results were tested for dependence on age, sex, spectacle correction from +2 to −5 D, and surround conditions such as room illumination, but the differences were not significant on the 0.05 level. Fig. 5 shows the

5 × 10⁻² W. This means that the above-mentioned power of the instrument at the cornea (3 × 10⁻⁸ W) allows a viewing time up to 10⁶ sec (300 hr) without interruption!
Fig. 6. a, Two examples of CSFs for diabetic retinopathy. 1, 76-year-old man; 2, 58-year-old woman. b, Example of CSF for neuritis of the optic nerve (22-year-old woman). Left eye nearly normal; right eye with electrophysiologically detectable loss of conductance of the optic nerve. Hatched areas in a and b are normal values.

Table I. Dimensions of glass plates (circular, diameter 10 mm) for an index of refraction of 1.506 and a magnification factor of 0.445

<table>
<thead>
<tr>
<th>Plate No.</th>
<th>Spatial frequency (cpd)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>0.16</td>
</tr>
<tr>
<td>3</td>
<td>2.2</td>
<td>0.22</td>
</tr>
<tr>
<td>4</td>
<td>3.3</td>
<td>0.35</td>
</tr>
<tr>
<td>5</td>
<td>6.0</td>
<td>0.60</td>
</tr>
<tr>
<td>6</td>
<td>8.2</td>
<td>0.88</td>
</tr>
<tr>
<td>7</td>
<td>14.3</td>
<td>1.46</td>
</tr>
<tr>
<td>8</td>
<td>22.1</td>
<td>2.30</td>
</tr>
<tr>
<td>9</td>
<td>34.5</td>
<td>3.65</td>
</tr>
<tr>
<td>10</td>
<td>46.3</td>
<td>5.0</td>
</tr>
</tbody>
</table>

mean CSF for all observers together with the 95% tolerance interval. The maximum CS corresponded to a spatial frequency of about 6 cpd (mean 6.3 ± 0.8), and the tolerance interval at this frequency was 0.4 log units. At 46.3 cpd the tolerance interval was 0.75 log units because of the smaller number of observers who could perceive gratings of this spatial frequency, which corresponds to a visual acuity of about 1.5. Table II shows the numerical values of the mean CS and of the lower 95% tolerance limit.

Repetitive CSF measurements of the same subject at different days and at different times.
times gave standard deviations of the means from 0.02 to 0.08 log units. Thus the relatively large tolerance interval of the normal CSF is caused mainly by the individually different CSFs.

Pathologic CS. Fig. 6 shows two examples of CSFs for diabetic retinopathy (a) and neuritis of the optic nerve (b). The two patients of Fig. 6, a, were 76 (curve 1) and 58 (curve 2) years old. Both patients showed a reduced CS over the whole frequency range, which corresponds to a low visual acuity. As an additional information we found a shift of the sensitivity maximum from 6 to 5 cpd (curve 1) and to 1.5 cpd (curve 2), which indicated increased central areas of the receptive fields (see Bryngdahl7) similar to dark-adaptation effects.

Fig. 6, b, shows the CSFs of a 22-year-old woman who suffered from neuritis of the optic nerve on the right eye with an electrophysiologically detectable loss of conductance of the optic nerve while the left eye was not affected. The loss of CS for low frequencies was dramatic, but that for the high frequency range was only small. This corresponds to a nearly normal visual acuity, so that the disease would not have been detected by acuity tests alone.

If no further information were given, the curves of Fig. 6, b, would suggest the following interpretations. (1) The loss of sensitivity of the right eye is not of optical but of neural origin because the sinusoidal test pattern is generated directly on the retina. (2) Since only one eye is affected, the neural defect is probably localized between retina and optic chiasm. (3) The afflicted neural pathway is responsible for the processing of foveal signals, since the tested retinal area includes the fovea and is of less than 5 degrees in diameter.

At present, no further diagnostic indication can be given, because there is only little statistical material.

Discussion

Comparisons with neural CS data from other authors are possible only for single observers, as in Campbell and Green1 and Kawara and Ohzu.8 The Campbell-Green data differ insofar as their best CS at 46 cpd (measured at 500 trolands) is 0.3 log units lower than our mean CS at that frequency (for 1000 trolands); the Kawara-Ohzu CS is 0.2 log units higher at 1000 trolands than ours but the same as ours at 180 trolands.

We have compared our neural CSF measurements for normal observers with overall CSFs reported by Derefeldt et al.9 who used a high-luminance oscilloscope at 120 cd/m². Their stationary vertical gratings were presented in a test field of 4.5 by 5.0 degrees at a distance of 143 cm, and contrast thresholds were determined by raising contrast from a subthreshold value as we did. In Fig. 7 their data for the groups of 20- to 40-year-old (filled circles) and over 60-year-old subjects (filled triangles) were replotted together with our mean CSs for 95 normal eyes (open circles). The curves were fitted by eye.

For spatial frequencies up to 6 cpd there was no substantial difference between neural
and overall CS, but for higher frequencies the overall CS was reduced by the optical properties of the eye.* This shows that for assessing defective contrast detection of neural origin, the irregularities of the optical media of the eye have to be taken in account. Spectacle correction may be sufficient in most cases, but defects other than spherical refractive errors or astigmatism that affects only one meridian may cause artefacts, especially in the upper spatial frequency range.

Up to now there is no evidence that neural CS measurements are specific for certain neural defects. But since the method is rather sensitive, it can be used as a screening test for the detection of neural defects of central vision if it is not too time-consuming. Our measurements of normal and pathologic CSFs shown in Fig. 6 lasted 20 min/eye (five measurements at 10 spatial frequencies), which is too much for clinical routine. We have therefore reduced the number of measurements to two and the number of spatial frequencies to five, which results in 5 min test time per eye. The measured CS values are compared with those of the normal observers, and the "loss-of-contrast" values are printed out in a semigraphical manner. Fig. 8 shows the loss-of-contrast curve for the patient of Fig. 6. The broken lines define approximately the lower 95% tolerance interval of Fig. 5. Resolution is 0.05 log units. The left eye (OS) has to be considered normal with a slight CS reduction at 46.3 cpd, whereas the right eye (OD) shows an increasing impairment of contrast detection toward low frequencies; the interpretation remains the same as for Fig. 6. Thus it is necessary to collect more data on this field, which will be easier with improved equipment. At present, we try to speed up our apparatus to get results in less time with perhaps even more precision.

REFERENCES

*Measurements made by Arundale10 with pattern-reversal presentation on a TV monitor at 100 cd/m² show about the same difference in CS at high spatial frequencies (1 log unit at 30 cpd) and about the same maximum value of CS (log CS = 2.3). Arundale's subjects show a maximum sensitivity at 3 cpd and a sensitivity enhancement of up to 0.2 log units for low frequencies <4 cpd, which is presumably caused by the nonstationary pattern presentation and makes the results not quite comparable with ours.

Fig. 8. Pathologic CSF of Fig. 6, b, replotted as loss-of-contrast curves (log units).