Sampling systems for visual field assessment and computerised perimetry

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SUMMARY Three successive stages in the representations of the visual image are studied by computations from the best available data. The results are embodied in projections, drawn automatically. These projections are related to the assessment of visual disability and the dimensions of lesions in the retina and visual pathway. Fields can be assessed visually with the aid of graticules or directly during computerised perimetry.

The complexity and variability of perimetric data present a serious obstacle to progress in ophthalmology owing to the difficulty in summarising or comparing field changes and assessing visual disability. It has therefore often been proposed that different parts of the visual field should be assigned a specific weighting so that a quantitative score could be obtained by calculation or planimetry.¹⁻⁴

Although some of these methods have won a well deserved popularity, they are based on the clinical judgment of their proposers or on surveys of professional opinion and have the disadvantage that an infinite number of alternative arbitrary proposals can be made. The merits of any one may remain forever a matter of opinion. It seems obvious therefore that there are some virtues attached to methods of quantification which are related to functional properties and dimensions of the visual system and determined by rigorous procedures.

The transformations which the visual image undergoes before it arrives as an encoded pattern of neural events in the cerebral cortex include 3 distinct stages which can be related to perimetric quantification. The image begins in environmental space, when it may be considered to be equally distributed over the solid angle subtended at the pupil by the visual field. It is projected on to the retina already subject to a relative compression of the peripheral regions, and finally in the visual pathways and striate cortex the foveal region has achieved its greatly enhanced representation. Surprisingly, none of these stages is proportionately displayed on the

conventional perimetric chart,⁵⁻⁷ which has retained a dominant role as a result of its use with mechanical self-recording perimeters.

Improved theoretical knowledge and the availability of techniques for more accurate computation and automatic drawing of charts have enabled us to re-examine this subject extensively to embody our findings in speedy and convenient methods of field quantification, and to present some observations on possible applications in computerised perimetry.

Theory and method

THE SOLID ANGLE

The extent of the visual field in terms of its solid angle has specific relevance to visual disability assessment. This may be illustrated by considering the solid angle in cases of contracted visual fields⁸ and is shown by the examples given in Table 1. On entering an unfamiliar room a subject with a contracted field must make a lengthy series of fixations, and orientation, mobility, and the recognition of extended objects or hazards are therefore very dependent on fixation strategy and short-term memory. The solid angle of a visual field is not proportional to its area on the conventional perimetric chart, and a chart which truly represents its size in solid degrees or steradians was described by Doesschatte.⁵ This has been achieved in the chart shown in Fig. 1A by making r , the radius of each circle, satisfy the equation

$$r(\theta) = K\sqrt{1 - \cos\theta},$$

where θ is the angular semidiameter of a polar zone of visual space and K is a constant determining the

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Table 1 *The quantification of various field defects according to the 3 selected criteria produces scores which are essentially independent from each other and from visual acuity*

Scotoma	Percentage loss			
	Solid angle	Retinal area	Channel capacity	Visual acuity
25° Diameter contracted field	96.1	96.4	49	0
10° Diameter central scotoma	0.63	0.58	25	70
Small peripheral detachment	2.3	1.0	0.3	0

size of the chart. The chart was produced on an ICL 1904 digital computer facility by calculating the required radii and then using these values in standard routines for a graph plotter output.

RETINAL IMAGE PROJECTION

The magnification of the image on the retina has long been known to be subject to nonlinearity in the radial direction.⁹ This distortion of the dimensions is greatest in the extreme periphery and may be significant in relation to the observed size of retinal lesions or in the assessment of retinal area for surgical procedures. The nonlinearity was further investigated by Drasdo and Fowler⁷ using a wide-angle schematic eye. The magnification around a circle of constant polar excentricity on the retina was determined. The product of radial and circular magnification was used to estimate the projection of the retinal area related to a solid degree in visual space, and a representative field chart was produced. It subsequently emerged that, owing to an error in formula 4 of Mandell and St Helen,¹⁰ a slight inaccuracy in the ray trace had occurred. This has been corrected, and although the correction has little effect on the retinal area chart it has been revised (Fig. 1B). The new equation for the corneal surface was $y^2 = 15.6x - 0.75x^2$, and the reciprocal of the derivative of this equation provided the tangent of the angle for the ray trace in the manner originally described. The modified chart permits an accurate estimate to be made of the size of a retinal area and may be useful for correlation with other data in surgical or electroretinographic studies.

NEURAL REPRESENTATION AND INFORMATION CHANNEL CAPACITY

The neural representation of the visual field at the level of the retinal ganglion cell layer, in the visual pathways, and striate cortex can be described by equations.¹¹ Quantification of the field in such terms is clearly valuable since it relates to the amount of

neural damage at a specified point in the visual pathways. The total information intake, or channel capacity, of an eye¹² can be estimated by using the same equations¹¹ to determine the number of bits per solid degree at any point in the visual field and integrating these values. The equations therefore provide a system of quantification which is of particular relevance to neuro-ophthalmological studies and perhaps the most generally valuable criterion of visual capability. This possibility was to some extent anticipated by Doeschatte⁵ in his somewhat tentative proposal of a chart based on integrated visual acuity, and by Crick,⁶ who commented on the ideal of a projection based on cortical area. For the purposes of the present study the calculation was based on information channel capacity but the quantification is in percentage terms which may be equally applied to neural representation.

The maximal potential information density $D(\theta)$ in bits per solid degree at any excentricity θ on a principal meridian of the visual field can be estimated from the following expression based on a more general equation.¹¹

$$D(\theta) = 3600(0.6[1 + s\theta\{1 + 3\theta^2 \times 10^{-5} + 8(s\theta)^{5.5} \times 10^{-10}\}]^{-2}) \dots \dots \dots (1)$$

where s is $(0.46 - 0.00043\theta)$, $(0.50 + 0.0019\theta)$, $0.62 + 0.0033\theta$ or $(0.66 - 0.0006\theta)$ for the temporal nasal superior and inferior portions of the principal meridians.

The solid angle $\Omega(\theta)$ subtended by any narrow concentric annular zone of visual space, which has a mean excentricity of θ , and inner and outer limits separated by $\Delta\theta$ is given by

$$\Omega(\theta) = \frac{360^2}{2\pi} \left[\cos\left(\frac{\theta - \Delta\theta}{2}\right) - \cos\left(\frac{\theta + \Delta\theta}{2}\right) \right] \text{solid degrees} \dots \dots (2)$$

The maximum information content $i(\theta)$ in any such annular zone is therefore $\Omega(\theta) \cdot D(\theta)$, the product of the values obtained from equations (1) and (2).

The cumulated maximal information content $I(\theta)$, for a visual field enclosed by an outer angular radius of θ is thus given by

$$I(\theta) = \sum_{n=1}^K \Omega \cdot (n \cdot \Delta\theta) \cdot D \cdot (n \cdot \Delta\theta) \dots \dots \dots (3)$$

where $K = \theta/\Delta\theta$.

During the process of numerical integration of $I(\theta)$ for the total field the program was arranged so that, whenever $I(\theta)$ reached certain predetermined amounts, the value of I and θ were stored and a quantity proportional to $\sqrt{I(\theta)}$ for these values

Fig. 1 Perimetric projections in which the visual field is proportionately represented according to 3 selected criteria: (A) the solid angle; (B) the retinal area; (C) information channel capacity and neural representation (right eye chart). Planimetry of plotted fields provides a percentage score ($1\% = 1 \text{ cm}^2$).

was used as the radial distance for lines on a perimeter chart. Since, however, equation (1) gives different values for each meridian of the visual field, the series of radii for each quadrant were used as the semiaxis dimensions in standard ellipse plotting routines of the computer. Each enclosed area on the chart produced by this program was proportional to its maximal information intake and the neural representation of the corresponding part of the visual field (Fig. 1C).

The nonlinear field charts (Figs. 1A, B, and C) can be used to assess visual fields quantitatively by planimetry of affected or surviving areas. But for speedy assessment of visual fields for clinical or research purposes a different approach is required. Esterman² provided a rapid method of quantification in the form of grids which could be applied to conventional perimetric charts.

To produce grids based on the 3 selected criteria, the computer was programmed to divide the visual field into cells of differing area, but equal weighting, according to each criterion, and to draw these superimposed on a conventional perimetric projection. This was achieved by similar numerical integration methods to those used to generate Figs. 1A, B, and C. But in the case of Fig. 1C, which was concerned with the highly asymmetric distribution of information channel capacity, or neural representation, the calculation from equation 1 was performed along oblique meridians as well as along the major ones, the values of s being found by interpolation from the parameters of the two adjacent 90° meridians and processed appropriately in a specially contrived program which culminated in the automatic drawing as previously described.

The cells in the grids were found to be a perceptual distraction when placed on top of the standard charts and were therefore removed, only a central dot being left to represent each 1% unit. These 1% cells were, however, initially constructed by the computer in smaller units, so that some freedom of choice was allowed to ensure that the composite 1% cell could be selected with the central dot in alternative positions. This limited degree of freedom in choice of the position of the dots, without varying their quantitative significance, permitted us to take account of anatomical and diagnostic factors such as the most probable discontinuities in retinal conditions or lesions of the visual pathway. The dot patterns which resulted are displayed in Figs. 3A, B, and C.

It was considered that Figs. 2 and 3 were worthy of separate reproduction in the form of transparent gratitudes, since the cell charts permitted a fairly precise assessment of small isolated areas, whereas

the dot charts provided a very quick method of assessing widespread field defects.

Discussion

The 3 criteria, based on projections of the visual image, are considered useful because of their independence and apparent validity. They are independent because the score on one criterion can never be predicted from another unless the actual field data are known. Their validity is considered to be axiomatic. If one is concerned with the assessment of visual disability resulting from the amount of field loss, the solid angle criterion is clearly valid. Since most vision during mobility is concerned with grossly super-threshold objects, it is primarily the actual size of the field that is involved. On the other hand, if one is concerned with the amount of visual information, the independent criterion of channel capacity commends itself. Neither of these displaces the importance of visual acuity, and the behavioural correlation of all are worthy of further examination in epidemiological studies on impaired vision.

When considering the assessment of retinal lesions, or of the percentage of retina involved for example in photocoagulation therapy,¹³ it is difficult to dismiss the validity of the retinal projection. The particular value of the neural representation criterion is evident when considering any lesion in the ganglion cell layer, visual pathways, or striate cortex. This might be used in conjunction with the neuroanatomical schemes¹⁴ showing the approximate projection along the optic nerve and radiations to assess the location and extent of a lesion more accurately at any specified point. It has also been appropriately applied to field studies of hereditary optic atrophy.¹⁵ If the independence and validity of the criteria are accepted, it might still be argued that they are not sufficiently different from existing methods to justify their use. This suggestion does not bear close examination, however, and even where the differences are small it would appear advantageous to use these appropriate criteria in order to gain the highest possible correlations in statistical terms where a particular hypothesis is being pursued.

The relationship of the criteria described to many existing methods of quantification is shown in Table 2. This emphasises previous views^{5,6} that the conventional chart does not represent any important criterion of the visual field appropriately. It can be seen that every criterion displayed shows a greater representation of the central area than the conventional perimetric chart. This must lead to the suggestion that the designers of computerised perimeters should display the data appropriately. The central

Fig. 2 Graticules for the assessment of fields plotted on conventional charts. (A) Each cell corresponds to 1% of the total solid angle. (B) The cells correspond to percentage units of functional retina, of which some 25% may be obscured by facial contours. (C) Channel capacity or neural representation. The computer, programmed to divide each octant into 1% annular sectors, created $\frac{1}{2}$ % cells around a central 4% circle and added the limits of the visual field.

Fig. 3 Dot graticules for speedy assessment of conventional field plots. Each dot scores as 1%.

Table 2 The percentage weighting falling within a given peripheral angle according to various field charts and assessment schemes. Note that every system of quantification gives a greater representation to the central fields than does the conventional field chart.

Weighting criterion	Radial peripheral angle			
	10°	20°	40°	70°
Conventional chart (area)	2.12	8.47	33.86	79.26
Solid angle	2.53	10.06	39.03	85.78
Retinal area	3.33	12.90	47.29	90.96
Walker (non-lin.)	3.69	12.30	43.67	86.85
Esterman grid	6.00	27.00	62.00	92.00
Crick (parabolic)	10.86	31.58	67.38	94.08
Spaeth <i>et al.</i>	15.39	30.77	61.54	94.23
Collenbrander	16.00	32.00	64.00	94.00
Channel capacity	45.16	67.37	90.23	99.65

portions of the field can be represented on a large scale when no mechanical linkage is necessary. The parabolic projection of Crick⁶ may well approximate towards a useful distribution of the displayed data, but the information in Fig. 2 provides a basis for suitable designs. Both central and peripheral fields can be adequately portrayed on such nonlinear charts without any increase in the total size of the record and with the minimal morphological distortion to which clinicians can easily adapt. In any event the emergence of more sophisticated computerised perimeters will permit the provision of several options in chart display.

Such systems could easily be programmed to utilise the sampling points shown on the graticules of Fig. 3 and to assess the criterion scores directly. This, however, might constitute an excessive extension of clinical procedures, so that the more appropriate strategy may be to organise the program to estimate each criterion as nearly as possible when any particular array of diagnostic sampling points is used. Estimates for the 3 criteria could then be printed out automatically on every perimetric record produced by a computerised system, independent of the particular diagnostic series used in the examination. The problems of visual estimation would thereby be effectively simplified and the data would be readily available on all records for statistical correlations. The data presented in Fig. 2 may thus assist instrument designers in incorporating advantageous features in computerised perimetry systems.

The present proposals relate to the distribution of weighting in the visual field but stop short of a complete system of quantification for disability assessment. They are clearly applicable to absolute scotomas, but the long-standing problems of

quantification of relative scotomas and binocular fields still require a solution, which is in the present state of knowledge essentially arbitrary. In accordance with conventional practice, however, a 3/330 target seems appropriate for solid angle assessment, and this could be applied binocularly. Similarly it appears that, if a relative scotoma is regarded as absolute when the target diameter is more than 3 times the normal value, the error in channel capacity assessments will probably be negligible.

Conclusions

Computer programs have been used to carry out calculations on visual fields and draw projections automatically. Three projections were selected for their functional significance and potential clinical value. These were based on (a) the solid angle of the visual field; (b) the projection of the field on the retina; (c) the information content of the visual field and its neural representation. Planimetry of the chart area permitted quantitative assessment on the basis of these criteria.

To avoid the tedious process of quantification the computer was used to prepare alternative projections in the form of graticules for speedy assessment of conventional field charts.

For disability assessment it was considered that projections (a) and (c) were most likely to be useful and less arbitrary than many established criteria. Criterion (a) was considered to relate to mobility where vision is mostly at grossly suprathreshold levels. Criterion (b) seemed the obvious criterion of overall visual capability (relating to tasks involving a large proportion of the channel capacity in normal vision, such as the location of objects). It was considered to be independent of visual acuity (which related to the observations of small isolated objects already located). For diagnostic and research purposes criteria (b) and (c) were considered most useful owing to their unprecedented facility for revealing the extent of lesions in the retina, visual pathways, and striate cortex.

It was concluded that it would be advantageous to incorporate an estimate of the scores for the 3 criteria in the printout of computerised perimetry systems. It also appeared appropriate that such field plots should be displayed on nonlinear charts.

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