Image processing of computerised visual field data

Frederick W Fitzke, David P Crabb, Andrew I McNaught, David F Edgar, Roger A Hitchings

Department of Visual Science, Institute of Ophthalmology, London
F W Fitzke

School of Mathematics, Actuarial Science and Statistics, City University, London
D P Crabb

Glaucoma Unit, Moorfields Eye Hospital, City Road, London
A I McNaught
R A Hitchings

Applied Vision Research Centre, City University, London
D F Edgar

Correspondence to:
F W Fitzke, Department of Visual Science, Institute of Ophthalmology, 11 Bath Street, London EC1V 9EL.

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Abstract

***Background*—Computerised perimetry is of fundamental importance in assessing visual function. However, visual fields are subject to patient response variability which limits the detection of true visual loss.**

***Methods*—A method of improving the repeatability of visual field data was demonstrated by applying techniques used in image processing. An illustrative sample of nine normals and nine patients with field loss was used. Two successive Humphrey fields were selected for each subject. Repeatability was defined as the standard deviation of the pointwise differences between sensitivity values of the reference field and repeat field. The field data were then separately subjected to Gaussian and median image processing filters and the repeatability was compared with the unprocessed field results.**

***Results*—Improvement in repeatability, by a factor of approximately 2, was demonstrated by both processes.**

***Conclusion*—These techniques may improve the reliable detection of loss of visual function using computerised perimetry.**

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Despite the widespread use of computerised perimetry, there remains a need to improve further the accuracy of the measurements which inevitably suffer from noise as a result of variability in patient responses and other factors. Computerised visual field data usually consist of numerical values which are spatially arranged on a regular matrix. Similarly, digital representations of medical images such as those from magnetic resonance imaging (MRI) are stored by a computer as numerical values on a regular matrix. This suggests that visual field data may be amenable to image processing which provides powerful techniques for noise reduction and quantitative analysis. We have demonstrated that visual field data acquired by the technique of fine matrix mapping can be treated as digital images and that the use of image processing techniques improved the repeatability substantially.[1 2] The standard deviations of the difference values from successive measurements were reduced by up to a factor of three. Here we investigate the use of image processing filters applied to Humphrey field analyser (HFA) 30-2 computerised visual field data to improve the repeatability of these measurements. We investigated two commonly used filters – a Gaussian (or normal filter) and a median filter.

The improvement in repeatability of the measurements was analysed using the technique described by Bland and Altman.[3 4] This method has been used to quantify the repeatability of measurements of the ocular components[5] and to determine the effects of weighting functions on visual field indices.[6] Briefly, the pointwise numeric differences between two visual fields is calculated and plotted versus the means of the pointwise values. The standard deviation of these difference values provides a measure of repeatability.

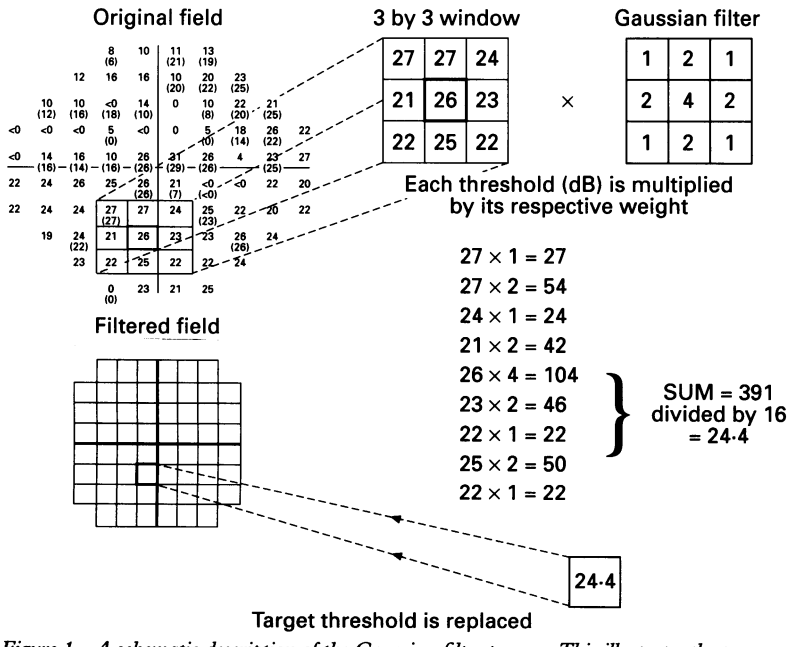

Figure 1 A schematic description of the Gaussian filter process. This illustrates the process at one location (stimulus coordinates −3, −15). Each value within the 3 by 3 window is multiplied by its fixed corresponding weight within the Gaussian filter. These values are averaged to generate a new, filtered value. This process, known as two dimensional convolution, is repeated at each location in turn across the field.

Methods

SUBJECTS AND DATA

Computerised visual field data were acquired using the HFA 30-2 program with the size III white stimulus in standard conditions. Nine ophthalmologically normal subjects were used. These were volunteers from a young student population. Mean age was 22 (range 20–26) years and mean refractive error was less than plus or minus 3 D. One eye was randomly selected and tested from each subject. Two successive fields (all 7 days apart) were selected for each subject. These are referred to as the reference and repeat fields respectively.

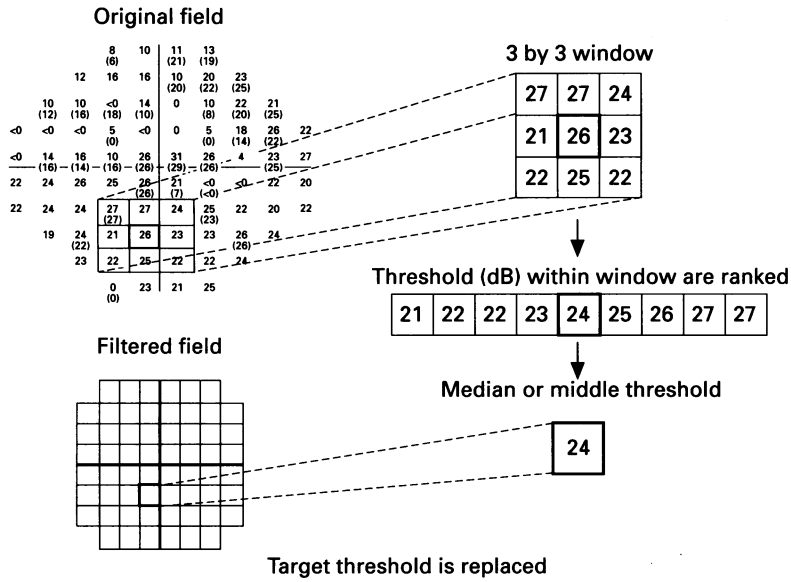

Figure 2 A schematic description of the median filter process. This illustrates the process at one location (stimulus coordinates −3, −15). Here the values within the 3 by 3 window are simply ranked in numerical order. The median of these becomes the new, filtered value.

Pathological visual fields were selected from a hospital database of patients with untreated normal tension glaucoma (NTG). NTG was defined as intraocular pressure (IOP) <21 mm Hg confirmed following IOP phasing, and optic disc appearance and field loss consistent with a diagnosis of glaucoma. Fields from nine eyes of nine NTG patients (mean age 61 years) were chosen to provide samples with a wide range of defect severity (range of MD −2·26 to −17·93 dB). An important selection criterion was to minimise the effect of interest fluctuation of any true glaucomatous deterioration. Therefore we chose reference and repeat fields from each of the nine eyes which showed minimum time between test dates (mean 17 days; range 7–31 days).

All subjects, including normals, had at least two fields examined before the defined reference field to minimise learning effects.[7 8]

STATISTICAL ANALYSIS

The visual field data were transferred to a PC and further analysed using purpose written software. The peripheral locations of the 30-2 grid (locations with x or y coordinates of +27 or −27) were excluded from further analysis. Each field was thereby reduced to a square 8 by 8 matrix of points with the addition of four corner locations computed using a weighted interpolation of the three adjacent thresholds. The two locations above and below the blind spot were excluded. Where a double determination at a test location was available from the HFA 30-2 results, an average of these two values was used.

The numerical difference (dB) between corresponding points of the first (reference) field and second (repeat) field was calculated for each location. The standard deviation of these *pointwise differences* between sensitivity values was used to define the *repeatability* between the reference and repeat fields. Also these pointwise differences were plotted against the mean of these values for each subject to illustrate their spread and distribution. These methods of evaluating repeatability, described by Bland and Altman,[3 4] are more appropriate and statistically valid than a correlation type analysis.

Following assessment of the repeatability of the raw data, filtered versions of each field were then generated using the image processing technique. Repeatability between successive filtered fields was compared with the unprocessed field results.

IMAGE PROCESSING TECHNIQUE

Spatial filtering is widely used in pixel based image processing.[9] It can be used to enhance, blur, smooth, or remove inherent *noise* from an image. The visual field is considered as a digital image composed of a matrix of light threshold values. A filter, which can be thought of as a small window, operating on a 3 by 3 neighbourhood is passed over each location in turn across the original field. Each target threshold (the central value in the 3 by 3 window) is replaced by a weighted average for the Gaussian filter (Fig 1) or by the unweighted median of the nine threshold values for the median filter (Fig 2). Partial neighbourhoods are used at the field edges and corners.

Results

Figure 3 shows a sample HFA grey scale representation of two visual fields from a patient with normal tension glaucoma. Figure 3A shows the reference field and 3B the repeat field measured 29 days later. The differences between the two fields are due to a combination of physiological sensitivity loss, other changes (for example, as a result of fatigue and learning effects) and variability in patient responses. The 8 by 8 matrix which was formed from these results as described above is shown in Figures 3C and 3D for the reference and repeat fields respectively.

The effects of the Gaussian filter are shown in Figure 3E and 3F for the reference and repeat fields respectively. Comparing the Gaussian filtered reference field (Fig 3E) with the unprocessed reference field (Fig 3C) shows that the overall shape of the region of visual field loss is retained with smoothing of smaller areas with local differences in measured values. The differences between the reference and the repeat fields are reduced in the filtered versions (Figs 3E and 3F) compared with the differences between the unfiltered reference and repeat fields (Figs 3C and 3D). Similarly, Figures 3G and 3H show the effects of the median filter.

The results for this patient are quantified in Figure 4. Using a graphical method described by Bland and Altman the pointwise numeric differences between the repeat and reference fields are plotted against the means of these values. Figure 4A shows the unfiltered results. It can be seen that the mean difference is very close to zero with little evidence of systematic departure from zero. Points below zero would

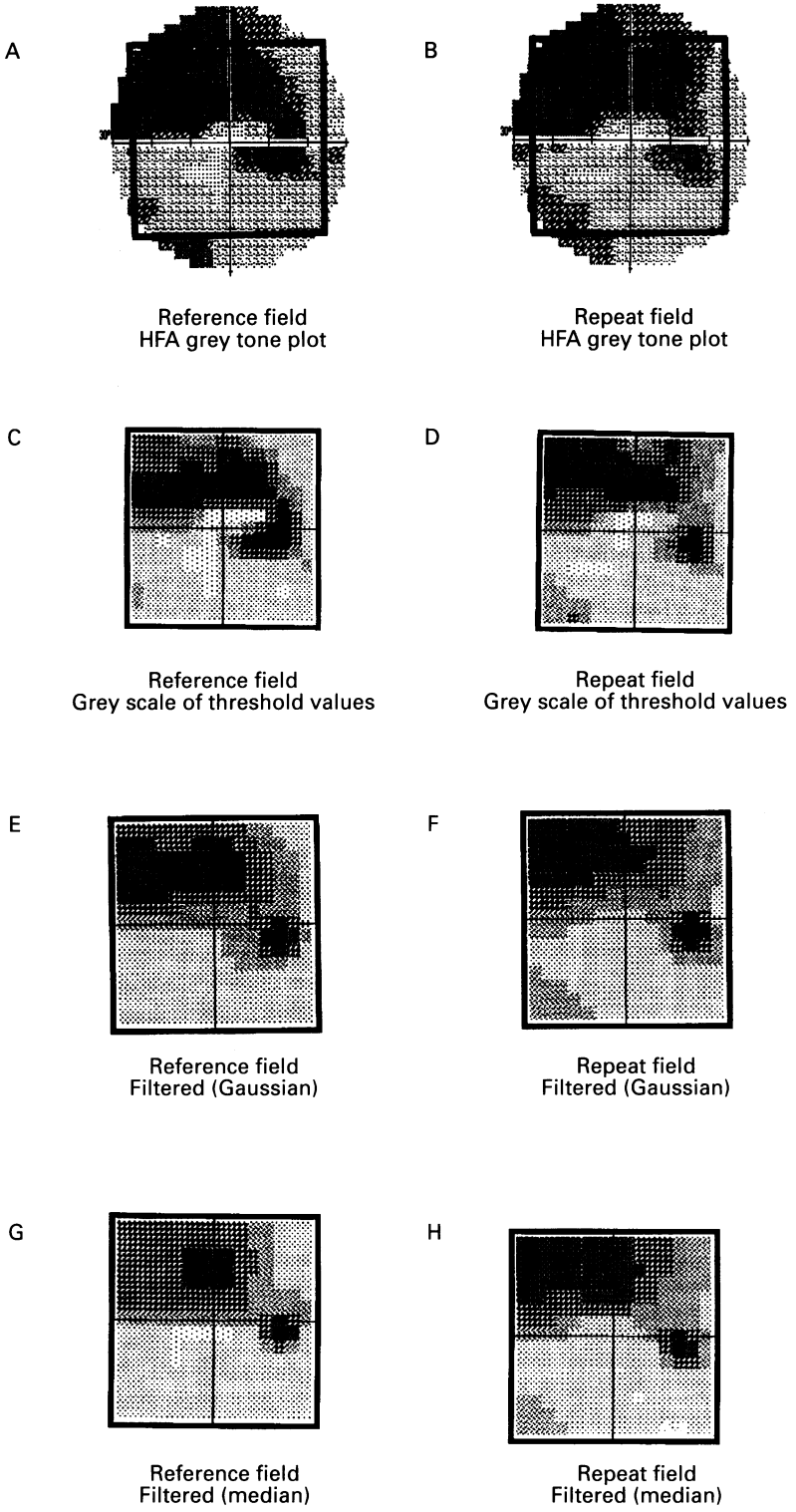

Figure 3 Grey scale plot of a glaucomatous visual field. (A), (C), (E), and (G) are the results for the reference field and (B), (D), (F), and (H) show the results for the repeat field. (A) and (B) show the normal HFA grey scale representation with the region outlined to undergo further processing. (C) and (D) show the completed 8 by 8 matrix of the central visual field. (E) and (F) show the same data after undergoing Gaussian filtering while (G) and (H) show the effects of the median filter.

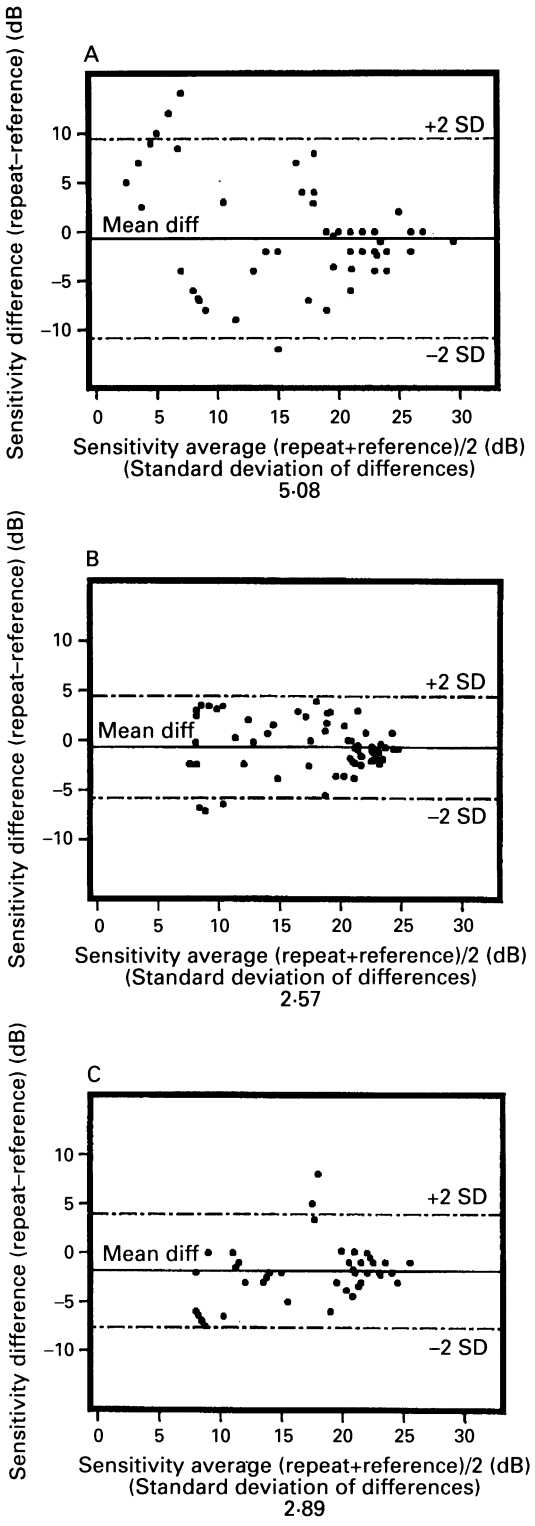

Figure 4 Plots of the pointwise numeric differences between the reference and repeat fields against the means of the pointwise values for the patient of Figure 1. The solid line represents the mean and the broken lines plus or minus SD of the pointwise differences. The values for the unfiltered data (A) and the median-filtered data (C) are integer values so some data points represent multiple, superimposed values. Gaussian filtered data (B) are calculated by averaging resulting in non-integer values. Hence there are fewer superimposed multiple values.

be expected if there was sensitivity loss while points above indicate sensitivity values were higher in the repeated measurements. Importantly there is considerable variability. A measure of this spread of the distribution is given by the standard deviation of the pointwise differences. This index is the measure of repeatability.

Figure 4B shows the results for the same data which has been filtered using the Gaussian filter. It is clear that the spread of the distribution has been reduced indicating smaller differences between the reference and the repeat sensitivity values. The repeatability indicated by the standard deviation of the difference values is much improved. The mean difference is again very close to zero suggesting little change between the two field measurements. The effects of the median

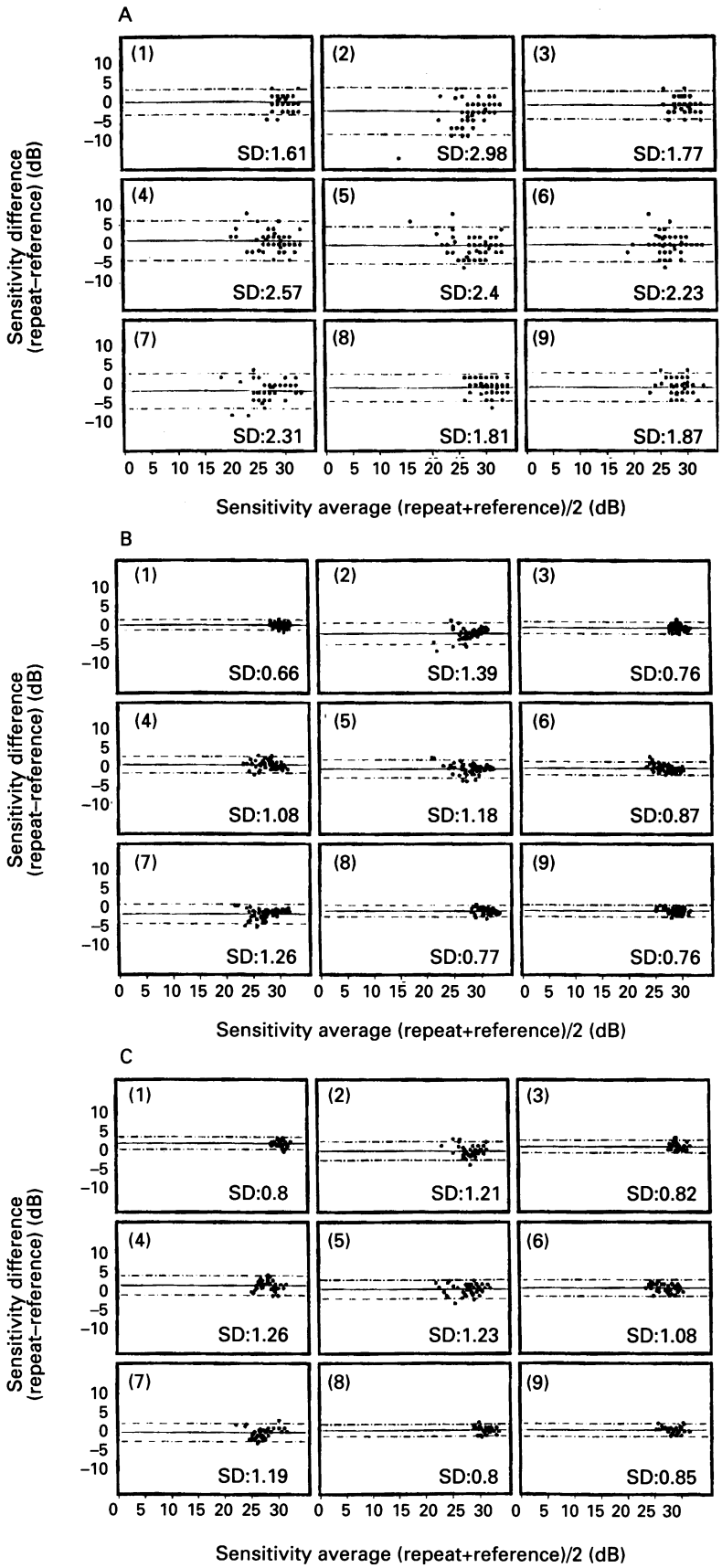

Figure 5 Summary data of pointwise differences versus means plots for the results from the nine normal subjects. (A) Shows the unfiltered results for subjects 1–9, (B) shows the results for the Gaussian filter, and (C) those for the median filter.

filter are shown in Figure 4C with similar results.

Summary results for the nine normal subjects are shown in Figure 5. Figure 5A shows differences versus means plots for each of the nine subjects with the corresponding standard deviations of these values. In these normals the mean sensitivity values are clustered near the normal values around 30 dB. The range of the standard deviations of the differences extends from 1·61 to 2·98 dB. Figure 5B shows the same results following Gaussian filtering. The reduction in the spread of values is substantial in all cases and illustrates the improved repeatability. The standard deviations are reduced by more than a factor of two (range 0·66 to 1·39 dB). Similar results are found for the median filtered sensitivity values.

Summary results for the nine NTG patients are shown in Figure 6. Figure 6A shows the unprocessed differences versus means plots for each of the nine eyes. In general, there is a wider distribution of mean sensitivity values as would be expected with glaucomatous visual field loss. The range of standard deviations of the difference values extends from 2·49 to 5·08 dB. This larger range of difference values suggests improved repeatability in these patients compared with the normal group owing to greater response variability. The mean differences are small suggesting little systematic change between these two measurements caused by learning, fatigue, disease progression, or other factors.

Figure 6B shows the same data following Gaussian filtering. There is a similar substantial improvement in repeatability in these patients compared with the normal subjects' results. The standard deviations of the pointwise difference values are reduced approximately by a factor of two (range 1·17–2·57 dB). Similar results are seen in the median filtered results.

Discussion

We have demonstrated how image processing techniques can improve the repeatability of computerised visual field measurements. The two filter processes illustrated, namely Gaussian and median, have substantially improved repeatability, by a factor of approximately two, in both our groups of normals and patients. This may be useful in more rapidly and reliably detecting earlier losses of vision.

The use of differences versus means plots (Bland-Altman plots) illustrates whether there is an overall change (bias), the distribution around the mean difference, and whether the spread is related to sensitivity. In these plots values below zero suggest sensitivity loss while values above zero indicate improvement. In these examples little change would be expected to occur because the time period between visual field measurements was small. The main effects of the image processing filters are to reduce the spread of the differences and therefore improve the repeatability of the measurements without altering the mean difference.

The application of image processing techniques to computerised visual field data can result in a dramatic improvement in repeatability with no additional cost in test time. This is unlike improvement in the precision of a measurement which can be achieved through repeated measurements, which requires additional data acquisition time. Since the standard

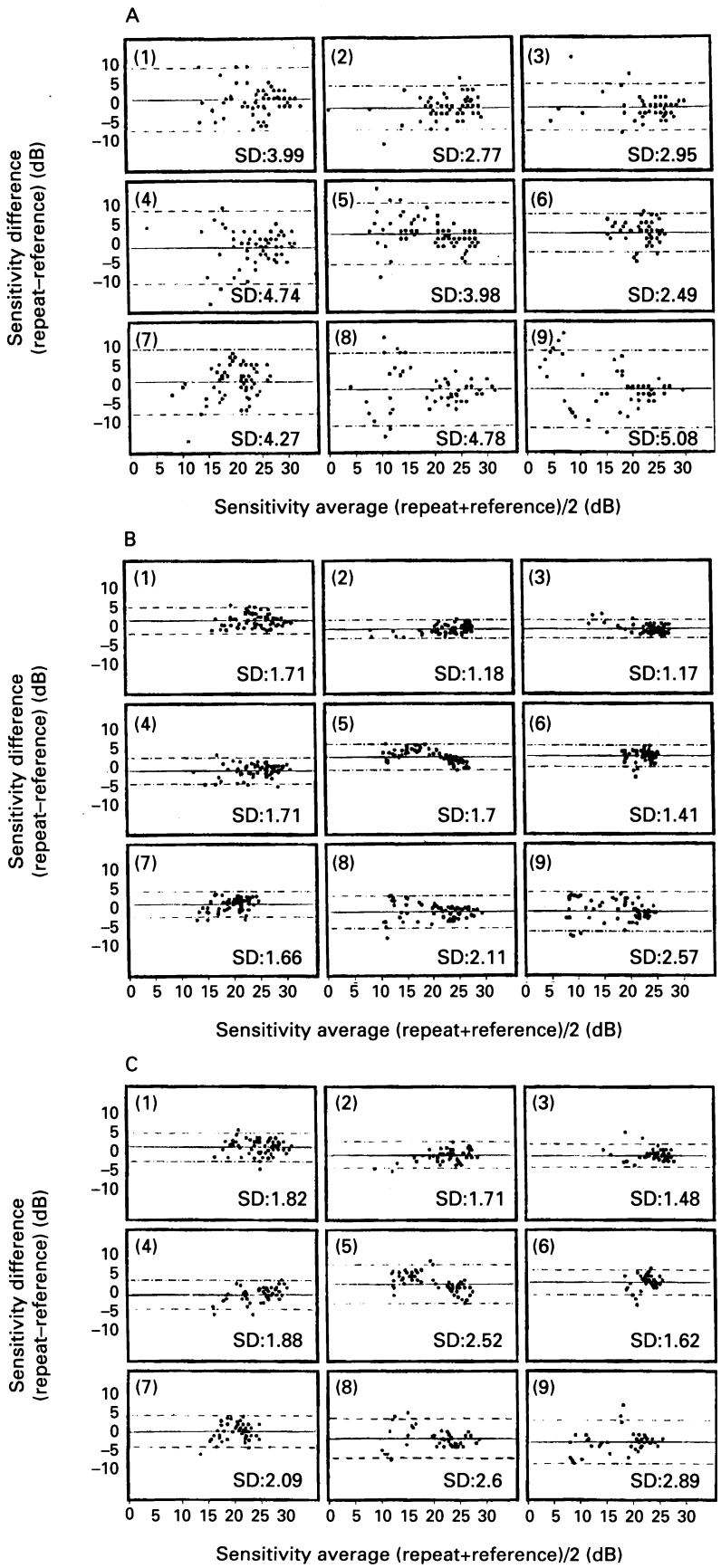

Figure 6 *Same as Figure 5 but for the results from the nine glaucoma patients.*

error of a measurement is a function of the square root of the number of observations, to achieve a twofold improvement by averaging the results of repeated measurements requires 2^2 repeated measurements. This would therefore require four repeated fields but then fatigue effects would become a factor. The twofold improvement we have achieved in repeatability is at no additional expense in test time. However, it does depend on spatial correlation of sensitivity values, and in fields with very small localised defects Gaussian image filtering may be less effective than other methods.

Since these image processing filters take advantage of spatial correlations in sensitivity values,[10] the improvement in repeatability would therefore be expected to be less if there is little spatial correlation. In addition, one effect of the Gaussian filter is to blur fine detail of visual field data such as that due to sharp edges of dense scotomas or small local defects. This effect is reduced with the median filter which has the property of relatively preserving this type of spatial detail. The median filter may be more useful in visual fields with abrupt borders of loss. However, for this small illustrative sample of normals and glaucoma patients the differences between the effects of the Gaussian and the median filters were small compared with the improvement of either filter relative to the unprocessed data.

Reducing test retest variability is important but the simple filtering processes illustrated here may actually reduce the pointwise sensitivity differences that we wish to detect. However, other filters or techniques from the large volume of image processing methodology available may preserve this information. Other types of image processing may have specific advantages – for example, the Sobel filter may be useful to detect edges of scotomas. Moreover, operations such as erosion or dilatation or combinations of these may be useful for enhancing some aspects of visual field data. We are currently investigating optimum image processing operations, including those customised specifically for the pathological configuration of the field, that reduce *noise* and detect important *signal* changes. Indeed we have shown that an image processing filter can improve the forecasting of visual field loss when combined with pointwise linear modelling of longitudinal field data.[11]

One application of these filtering techniques may be as a quantitative descriptor of the degree of localised versus diffuse loss. They may prove useful in characterising the spatial properties of visual field loss, since the degree of spatial correlation can be quantified. Moreover, an important implication of the processing described here is that the pointwise variability extracted by spatial filtering can actually be quantified.[12] This allows for a new approach to estimating the level of variability within visual field data which is fully described in a companion paper.[13]

In summary, we have described two types of image processing filter which result in an improvement by a factor of two in the repeatability of computerised threshold static perimetry data. The type of image processing filter which is most effective may depend on several factors. The spatial separation of the test locations would be expected to contribute, and the effectiveness of the process depends on the degree of spatial correlation of sensitivity.

Optimum performance may be enhanced through the use of image processing tailored to the type of visual field loss, and further investigation of other processing techniques may yield further improvements. Since image processing can be carried out post hoc this is achieved at no additional cost in test time. The resulting improvement of the repeatability of the measurements may be a useful technique to increase the sensitivity and specificity of detecting visual field loss.

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