Quantification of Glaucomatous Visual Field Defects with Automated Perimetry

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A method to quantify different glaucomatous visual field defects is presented. Three visual field indices are calculated: the short-term fluctuation, the mean defect, and the corrected loss variation. The method was applied to visual fields tested with program J0 on the Octopus automated perimeter. The indices of 130 glaucoma suspects and 50 glaucoma patients were compared with 100 normal controls. The indices provide good detectability of visual field defects and easy follow-up. Invest Ophthalmol Vis Sci 26:176–181, 1985

Perimetry has been the standard test of visual function in glaucoma for decades. In the last few years, it has been suggested that perimetric defects are preceded by other psychophysical disturbances such as color vision discrimination,[1] spatial and flicker contrast sensitivity[2] as well as by electrophysical functions such as the pattern VEP.[3] Morphologic changes such as disc haemorrhages[4,5] and defects in the nerve fiber layer[6] also have been claimed to precede visual field damage.[7] Histologically extensive nerve fiber loss has been determined in glaucoma suspects with so-called "normal visual fields."[8]

The question arises, therefore, whether the differential light sensitivity that is measured in perimetry is, indeed, less sensitive to pressure damage than other visual functions or whether the methods applied to measure and analyze the differential light threshold are not sensitive enough.

Before one can study this question, though, one must reevaluate the methodology for measuring and analyzing visual fields in glaucoma patients. The normal visual field has to be defined and one has to know (1) what the relevant parameters in a glaucomatous visual field are, (2) what their normal values are, and (3) how to compare the measured parameters with the normal values. The purpose of this study is to evaluate the relevant parameters, to develop a method to quantify them, and, finally, to test this method on a larger group of normal and glaucoma patients in order to compare them.

The large variety of possible visual field defects in glaucoma can be categorized into three major groups: (1) Local defects—This can be one deep scotoma as shown in Figure 1a, several small depressions of the sensitivity scattered over the visual field (Fig. 1c), or a nasal step. (2) Diffuse depression of the differential light sensitivity[12] (Fig. 1b). (3) Increased short- and long-term threshold fluctuations.[10,11] These different types of damage often are combined.

In line with this concept, we developed a method to quantify such defects and applied it in the design of the J0 program of the Octopus-automated perimeter. From the data so obtained, we calculated parameters that we call visual field indices.

The following indices were calculated for each visual field: short-term fluctuation (SF); mean defect (MD); and corrected loss variation (CLV). Table 1 shows the mathematic formulas for calculating these indices from data represented schematically in Figure 3. These indices resemble laboratory results. The clinician using these indices, therefore, will get to know their clinical meaning. The basic clinical significance of the indices is as follows:

SF is the scatter observed during one visual field test. In normals it is between 1 and 2 dB. It is increased in disturbed visual fields[9] but also in glaucoma suspects with otherwise normal visual fields.[10,11] It also is increased by impaired cooperation. The latter influence can be estimated by the rate of false replies in catch trials.[9]

MD in normals is scattered around zero. It is increased by any kind of visual field defect, but, in

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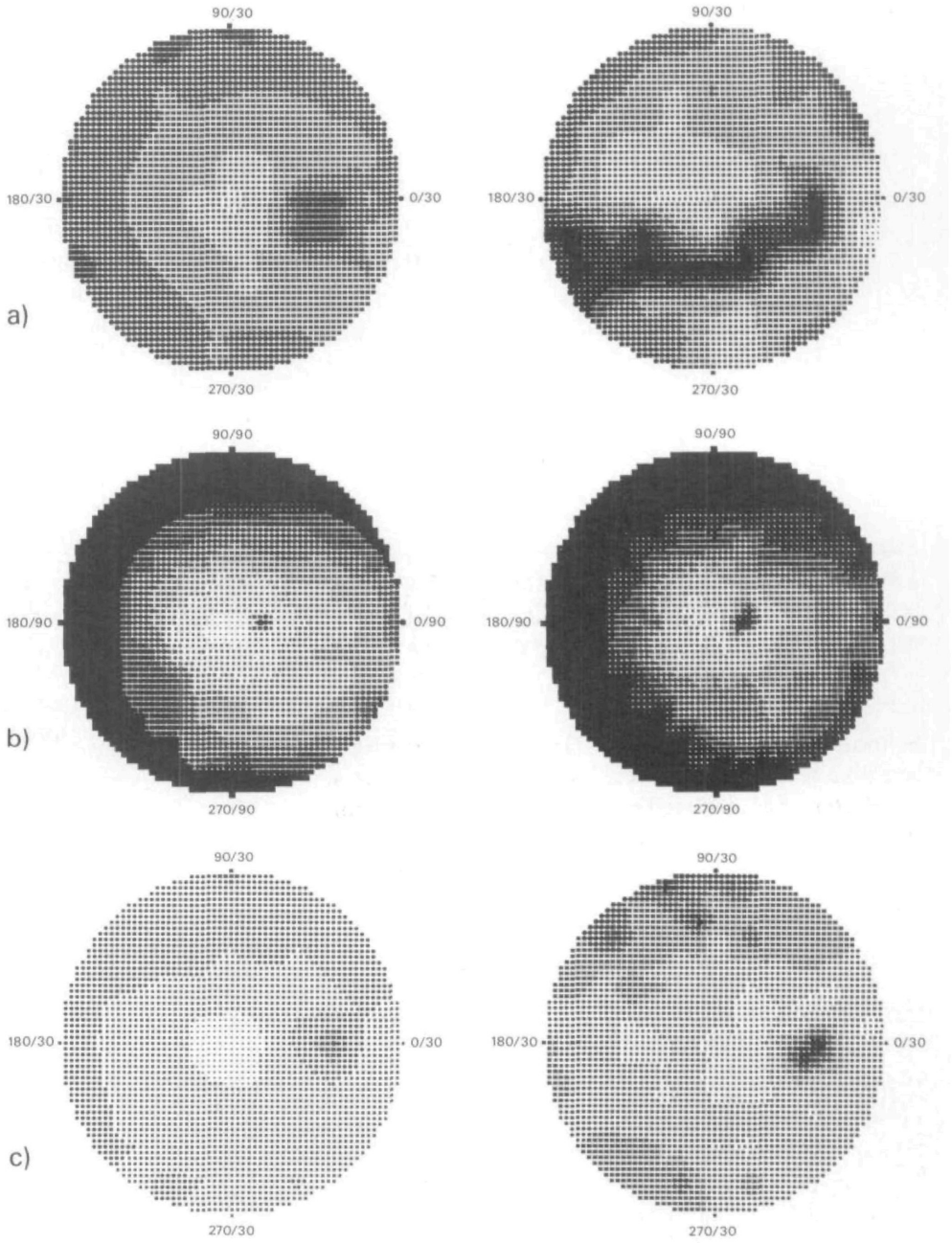


Symb.									
dB	51–36	35–31	30–26	25–21	20–16	15–11	10–6	5–1	0
asb	0,008–0,25	0,31–0,8	1–2,5	3,1–8	10–25	31–80	100–250	315–800	1000

Figure 1. a, Octopus program 31 of the right eye of a 82-year-old healthy man (upper left) and of a 81-year-old man with glaucoma (upper right) showing a typical nerve fiber bundle defect. **b**, Octopus programs 21/31 of the right eye of a 45-year-old healthy man (left) and of a 43-year-old man with elevated IOP (right) who has a diffusely depressed differential light sensitivity. **c**, Octopus programs 31/32 of the right eye of a 58-year-old healthy woman (lower left) and of a 58-year-old patient with elevated IOP (lower right) who has several shallow scotomas scattered throughout the visual field.

contrast to CLV, relatively little by small scotomas and very much by diffuse depression of the differential light sensitivity. Such a diffuse depression can be observed in several conditions, such as cataract, but also in glaucoma.[12] MD is very little influenced by the SF. The follow-up of the MD allows an approximation of the homogeneous component of the long-term fluctuation,[13] which is increased in glaucoma suspects particularly.[10]

CLV is an index of the local nonuniformity of a visual field defect. It is around zero in normal visual fields as well as when the differential light sensitivity

Table 1. Calculation of the three indices

Mean defect:

$$MD = \frac{\sum_{i=1}^{m} (z_i - \bar{x}_i)}{m}$$

Short-term fluctuation:

$$SF = \sqrt{\frac{\sum_{i=1}^{m} \frac{\sum_{k=1}^{n} (x_{ik} - \bar{x}_i)^2}{n-1}}{m}}$$

Corrected loss variation:

$$CLV = \frac{\frac{n \sum_{i=1}^{m} (\bar{x}_i + MD - z_i)^2}{m-1} - (SF)^2}{n}$$

The number of test locations tested is m, the number of repetitions (phases) is n; x_{ik} is the measured differential light sensitivity of test location i in phase k; and z_i is the age corrected normal value of test location i. In the program J0 on the Octopus automated perimeter, m = 49 and n = 2.

is uniformly depressed. This index is increasingly sensitive to any kind of real local defect including a nasal step. Local deviations due to scatter do not influence the CLV at all, or very little, due to the fact that this index is corrected using the SF. This is of special interest as it is very difficult to separate true beginning scotomas from deviation due to scatter by subjective interpretation of a visual field plot.

Materials and Methods

Included in this study were 200 visual fields of 100 normal eyes of 100 subjects, 334 visual fields of 190 eyes of 130 patients with suspected glaucoma and 89 visual fields of 67 eyes of 50 glaucoma patients. The latter separation was made on the basis of several abnormal manual and automated visual field tests prior to this study. Patients with large visual field defects were not included.

All normal volunteers had no known eye disease, had 20/30 vision or better, had less than 3 D of spherical correction, and had less than 2 D of cylindric correction. They were informed about the study purpose. The visual fields of the patients, however, were determined for clinical purposes and analyzed for this study retrospectively.

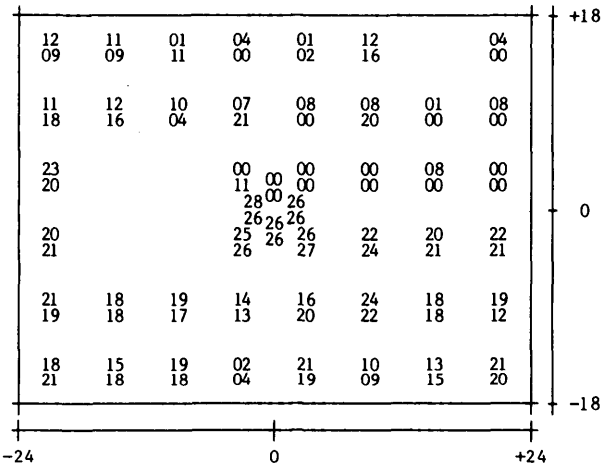
To test reproducibility, we selected 167 eyes that had two visual field tests less than 1 month apart. The mean age of the normals was 48 ± 17 years and of the glaucoma suspects 50 ± 11 years. The age of the glaucoma patients was slightly higher, the mean being 55 ± 8 years.

The visual fields were plotted with program J0 on the Octopus. An example of a numerical printout produced by program J0 is shown in Figure 2. It measures the differential light sensitivity twice at 49 locations, which extend 21 deg from fixation horizontally and 15 deg from fixation vertically. The blind spot is omitted, and there is a concentration of five points at and around fixation. This program has been described in detail elsewhere.[14,15]

The three indices already mentioned were calculated from each visual field test: the overall mean deviation from the normal age-corrected value stored in the Octopus computer, called mean defect, MD; the overall mean scatter that we call short-term fluctuation, SF; and the corrected loss variation, CLV. The basis for calculating these indices is the following model:

$$x_{ijk} = z_{ij} - MD_j + TL_{ij} + E_{ijk}.$$

x_{ijk} is the differential light sensitivity at the test location i of the patient (eye) j in phase k; z_{ij} is the normal value at test location i, age corrected for



MULTIPLE DETERMINATIONS

COORD. X = -15 / Y = 15

PHASE 1:	15	15	13	15	13
PHASE 2:	21	19	15	12	15

COORD. X = 0 / Y = 0

PHASE 1:	26	27	27	27	26
PHASE 2:	24	24	25	26	25

Fig. 2. Example of a numerical grid as measured using OCTOPUS program J0. Forty-nine locations are tested. The grid interval is 6 deg, and the blind spot is omitted. In addition, the fixation point and four pericentral locations with an eccentricity of 2 deg are included. Forty-seven locations are tested twice. Two points ((x,y = −15, 15) and the fixation point) are tested ten times.

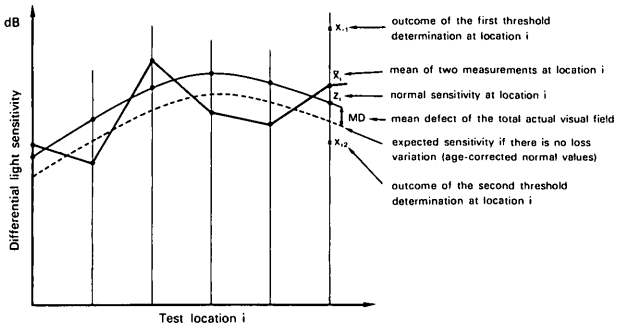


Fig. 3. Schematic illustration of the different values used for the calculation of the three indices: SF, ML, CLV; x_{i1} is the differential light sensitivity in phase 1; x_{i2} in phase 2 at the test location i; and z_i is the age-corrected normal value of the differential light sensitivity at test location i. MD is the overall mean defect of the differential light sensitivity.

patient j; MD (mean defect) is the overall mean deviation of patient (eye) j from the normal values; TL_{ij} is the influence on the threshold of the test location i of patient j; CLV (corrected loss variation) is the component of variance of the factor TL; and E_{ijk} is the unexplained variance which we call $(SF)^2$. The formulas for the calculation of the indices are derived from this model and are listed in Table 1. The values used for the calculation are shown schematically in Figure 3.

Results

The mean values of the MD and the CLV in normals, glaucoma suspects and glaucoma patients are listed in Table 2. As glaucoma eyes were differentiated from glaucoma suspects by having scotomas in the previous visual field plot by subjective interpretation, it is not surprising that glaucoma patients had a larger CLV (17.23 ± 26.45 $[dB]^2$) than normals (1.50 ± 2.60 $[dB]^2$). It is of interest, however, that the glaucoma suspects also had a slightly larger CLV (2.63 ± 6.98 $[dB]^2$) than normals, although this difference was statistically insignificant.

The distribution of CLV in normal eyes is shown in Figure 4 with the help of a probability plot. It is not age related up to about 65 years (Fig. 5). In some elderly persons however, the CLV can be much larger, indicating that in these cases the profile of the island of vision is no longer smooth, even in the absence of a cataract or pressure elevation. A subsequent biomicroscopic examination of the eyes with extreme CLV values showed, however, abnormalities on the retina or the optic nerve head in the majority of such cases. Thus the normal range of our data corresponds to that of an average and not to a highly selective one.

Table 2. Mean ± SD of visual field indices mean defect and corrected loss variation

	Mean defect	*Corrected loss variation*
Normals	0.20 ± 1.50 dB	1.50 ± 2.60 $(dB)^2$
Glaucoma suspects	2.00 ± 2.63 dB*	2.63 ± 6.98 $(dB)^2$
Glaucoma eyes	4.38 ± 6.02 dB*	17.23 ± 26.45 $(dB)^2$ *

* Significantly different from normals ($P < 0.05$, Mann-Whitney U-test).

The eyes with elevated IOP (Fig. 4b) can be divided into two groups with the help of the CLV, the first without and the second with local defects (scotomas or nasal step). The first group has a CLV like that of normal eyes and the second group has a CLV larger than seen in normals.

Although there is, as expected, a correlation between MD and CLV (R = +0.66), there are eyes with larger

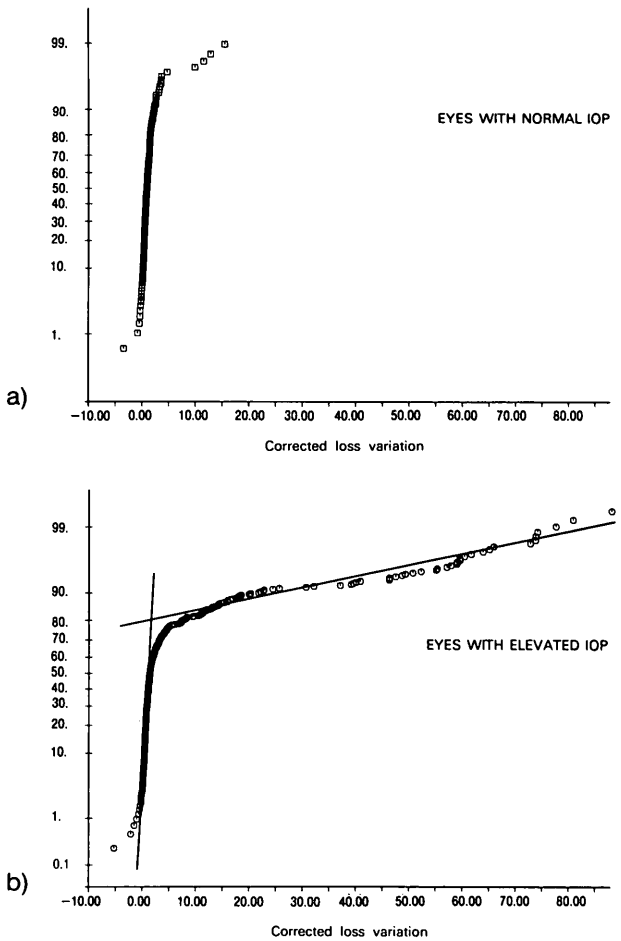


Fig. 4. Cumulative relative frequency curve of the CLV **a**, in normals and **b**, in patients with elevated IOP. The patients with elevated IOP are composed of two groups, one with a CLV like normals and the other with a large CLV.

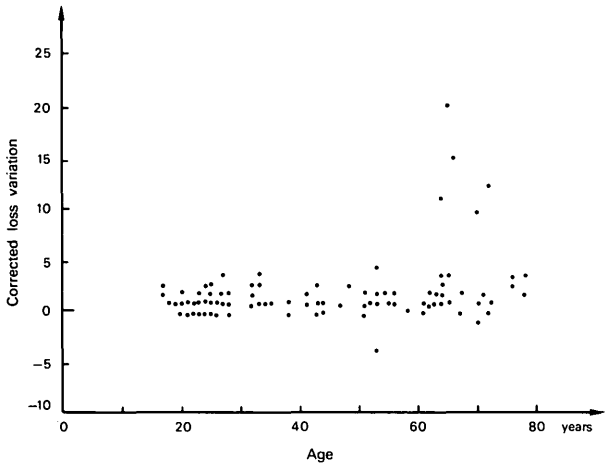


Fig. 5. Age-relationship of the CLV in normals. There is no increase in the CLV up to about 65 years. Some elderly persons, however, had a high CLV without either elevated IOP or a cataract.

MD without abnormal CLV, and some patients showed larger CLV without abnormal MD (Fig. 6). The former are patients with diffuse uniform depression of the differential threshold, while the latter are patients with small scotomas in otherwise normal visual fields. The SF was correlated with the CLV (R = +0.56) and with the MD (R = +0.64).

In 167 eyes the indices of a first visual field test were correlated with the indices of a second test. The correlation coefficient R for the MD was 0.88, for the CLV 0.86, and for the SF 0.77. Further studies on the reproducibility of the indices are underway.

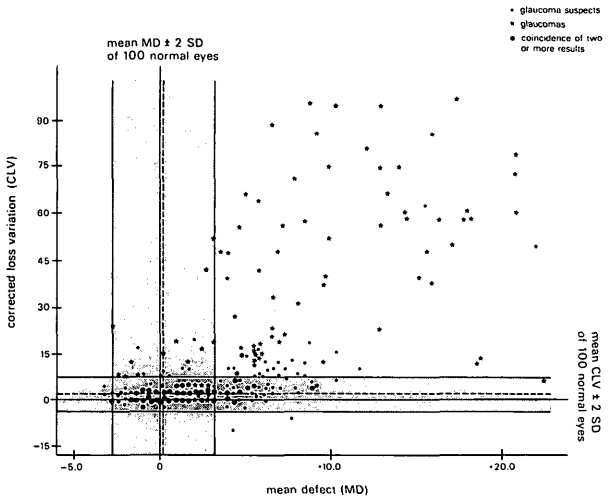


Fig. 6. The relationship between MD and CLV in patients with elevated IOP. The gray areas show the range of the values of our 200 visual fields of 100 normal controls. There are a considerable number of patients with a pathological MD and a CLV in the normal range. These are the patients with a pure diffuse depression of the sensitivity.

Discussion

A discrepancy between the findings of perimetry on the one hand and other psychophysical tests as well as morphologic signs on the other has been observed in glaucoma eyes. It has even been claimed that the early localized defects in the visual field are already late symptoms of the disease.

We reevaluated, therefore, the methodology used to analyze visual fields in glaucoma patients and glaucoma suspects. Although small paracentral scotomas as well as scotomas with the shape of nerve fiber bundles and nasal steps are the typical visual field defects in glaucoma, we can observe also less specific changes such as increased short- and long-term fluctuation,[10] a diffuse depression of the differential light sensitivity (Fig. 1b) as well as shallow scotomas scattered over the visual field (Fig. 1c). It was the intention of this study to collect and quantify all this specific and nonspecific information in order to compare it with a normal population.

We introduced three visual field indices (SF, MD, CLV), which can be computed by the host computers of automated perimetry. SF is an index of the scatter of the differential light sensitivity observed during one visual field test, MD is a index for any kind of defect but, in the early stage, especially for diffuse damage, and CLV finally is an index of local damage.

We reported earlier the significance of an increased SF in glaucoma suspects.[10] The long-term fluctuation is even more often increased. The latter also can be approximated by the variation of the MD over time.

The MD in our 100 normal controls was approximately zero, indicating that the normal values stored in the Octopus computer memory are correct, at least on the average. As expected, MD was increased in those patients with glaucoma and glaucoma suspects. However, it is of interest that MD is increased in a considerable number of eyes while CLV is still in the normal range, ie, without the presence of scotomas. This is consistent with previous reports of diffuse damage in glaucoma. The diffuse damage has been reported previously to correlate with the error score in color vision[16] and the progression of this diffuse damage was correlated with the fluctuation of IOP.[12]

In normal controls, CLV scattered slightly above zero. We like to emphasize that our normal population represents an average population having no ocular complaints, good visual acuity, and normal IOP. Selecting only subjects having an entirely normal morphology would reveal another range of normal values. We are dealing with such questions in further studies.

In patients with elevated IOP one easily can separate out two groups, one without scotomas (CLV in the

normal range) and one with probable scotomas (CLV out of the normal range).

Although the differential light sensitivity is age related,[17] MD and CLV are not age related in normals due to the fact that the normal values stored in the memory of the Octopus computer are age corrected. However, in some elderly normals the CLV was increased mildly, indicating that the island of vision in these cases no longer has a smooth profile for reasons that have to be evaluated.

The comparison of two visual field tests on the same eye yielded a good reproducibility of these three chosen indices. We know that the reproducibility has natural limitations due to long-term fluctuation.

Our study has shown that the calculation of these three visual field indices can be performed without additional load for the patient or for the perimetrist. They permit an easier and more accurate analysis of a visual field than the merely subjective interpretation of a visual field plot. They facilitate follow-up and allow a direct quantitative comparison with normal values, as well as with the outcome of other psychophysical tests. They permit us to distinguish between visual fields having more diffuse damage from ones exhibiting more localized damage. The new parameters then may be helpful not only for detecting and characterizing early damage but also in detecting progression. We like to emphasize that we need more studies to establish better normal values and to validate the clinical usefulness of these parameters. Studies considering the possible effect of fatigue, pupil size, cataract, and other ocular diseases are also in progress. We are further testing the application of this kind of quantification on the OCTOPUS routine programs, such as 31 and 32.

Finally, we like to emphasize that ignoring the nonspecific visual field changes, one can get a false impression of "normal visual fields" in a considerable number of patients with suspect glaucoma. A search for localized field defects alone not surprisingly shows that the other psychophysical parameters often show abnormalities in patients with so-called "normal visual fields." The methods described in this paper might thus be helpful both for research and for clinical practice.

Key words: automated perimetry, glaucoma, visual field, visual field indices

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