Reprinted from: OPHTHALMOLOGY • INSTRUMENT AND BOOK SUPPLEMENT 1987

Enhancement of Fundus Photographs Taken Through Cataracts

ELI PELI, MSc, OD,*†§ BERNARD SCHWARTZ, MD, PhD*

Abstract: Image-enhancement techniques can aid the clinician in evaluating fundus pictures taken through cataracts. The degradation of the fundus image by cataracts has been described as low-pass filtering. Means to partially overcome this degradation using homomorphic filtering and adaptive enhancement are presented. The clinical value of these enhancement techniques is demonstrated with two cases of progressive glaucoma and cataracts. [Key words: cataract, enhancement, fundus photographs, glaucoma, image processing, retina.] Ophthalmology 94(S):10–13, 1987

Fundus photographs are used routinely in ophthalmic practice for diagnostic and follow-up purposes. The advantages of using photographs rather than clincial notes or hand-drawn diagrams in evaluating eye diseases are obvious. The value of photographs is even greater when evaluating the subtle fundus changes that occur over time in many slowly progressing diseases. Because some of these changes are difficult to observe directly, various objective measurement techniques[1,2] as well as automated computerized image-processing techniques[3–6] have been introduced. These techniques may increase the use of fundus photographs because the images can be analyzed more rapidly and objectively by the computer.

Since many eye diseases are associated with age, the quality of fundus photographs is frequently reduced because of light scatter resulting from cataracts and other ocular media turbidity.[7] Degradation of the image by a cataract greatly impedes both visual inspection of the photograph and automated image processing.

Various enhancement techniques have removed the light cloud cover from satellite or aerial photographs of the earth to expose objects beneath the cloud.[8,9] One of these techniques, adaptive enhancement, has been effective in enhancing images seen through simulated cataracts.[10] Because the improvement of fundus photographs taken through cataracts appears to be a similar situation, we applied computerized image-enhancement techniques in this study to degraded fundus images.

From the Department of Ophthalmology,* Tufts University School of Medicine, New England Medical Center, Eye Research Institute of Retina Foundation,† and the Department of Ophthalmology,§ Harvard Medical School, Boston.

Supported in part by grants EY05450 and EY05957 (EP) from the National Eye Institute and a grant from Research to Prevent Blindness (BS).

Reprint requests to Eli Peli, MSc, OD, Department of Ophthalmology, Box 450, New England Medical Center, 750 Washington Street, Boston, MA 02111.

MATERIALS AND METHODS

Color slides (35 mm) of the fundus with the optic disc in the center were digitized. The digitization consisted of three successive scans, one each through red, green, and blue filters. Only the green scan that provides the best contrast for blood vessels was used. The image was transformed into a video signal using the Datacopy (Mountain View, CA) camera. The analog video signal was then digitized, and the data were stored on computer disks. The original and processed images were displayed on the DeAnza (Beverly Hills, CA) IP-5000 image-processing unit.

The image was described in the computer as a two-dimensional array, F(i, j), where i and j were the horizontal and vertical coordinates of each picture element, respectively. The numerical value of F(i, j) for every i and j represented the grey level of the corresponding point of the image. Applying specific mathematical operations to these numbers may be used to obtain a different set of numbers representing an enhanced image. One of the common enhancement techniques involves spatial filtering, which modifies the value of picture elements according to the spatial frequency content of image structures. The rate of change of grey levels with distance is a measure of spatial frequency. Sharp edges or thin lines are composed of high-spatial frequencies. Slow variations of grey levels that extend over most of the image are composed of low-spatial frequencies. Mathematical operations termed *high-pass filters* can enhance the high-spatial frequencies and reduce the low-spatial frequency content of the image, resulting in increased visibility of structures composed of thin lines or sharp edges of low contrast.

The effect of cataracts on scenes visualized by the patient as well as on the image of the fundus as seen by the clinician has been described as low-pass filtering.[7,11] Under such conditions, the high-spatial frequency content of the image is reduced, and thereby decreases the contrast and visibility of fine detail in the image. Therefore, various types of high-pass spatial filtering techniques are expected to counter the effect of the cataract and enhance the image. In addition, features of interest in fundus photography such as blood vessels, nerve fiber layer, and retinal lesions represent high-spatial frequency content of the image; thus, high-pass filters increase their visibility. We applied two different techniques of enhancing the high frequency of the image, homomorphic filtering[9] and adaptive image enhancement.[8]

Homomorphic filtering has been applied successfully to enhancement of images degraded by shadows or atmospheric haze clouds. This technique assumes that the degrading interference is multiplicative with the image and contains mostly low frequencies. The recorded image F(i, j) is described as:

$$F(i, j) = I(i, j) \cdot E(i, j)$$

where I(i, j) is the reflectance characteristics of the image (composed mainly of high-spatial frequencies), and E(i, j) is a slowly changing degrading field of variable intensity (low-spatial frequencies).

However, the linear high-pass filtering techniques mentioned earlier cannot be applied directly to enhancement of the reflectance if the reflectance is multiplied rather than added to the low-frequency content of the image. This difficulty can be overcome by applying the following principle: the logarithm of multiplication of two elements is equal to the sum of the logarithms of the two elements. Thus, taking the logarithm of F(i, j) yields:

$$\log [F(i, j)] = \log [I(i, j)] + \log [E(i, j)]$$

which is an additive noise expression and, therefore, may be successfully enhanced with conventional linear high-pass filters. This is done by transforming the logged image into the frequency domain using the fast fourier transform (FFT) and applying a high-pass filter with a Gaussian profile in the frequency domain. The filter used amplified the highest spatial frequencies five times and attenuated the lowest spatial frequencies to 0.2 of the original value. The filtered image is then retransformed to the space domain with the inverse FFT and is antilogged and displayed on the screen.

The adaptive enhancement algorithm was developed for images degraded by cloud cover or shadows, or both.[8] The adaptive nature of the algorithm is a result of changing the processing parameters at every point of the image based on its local characteristics. The image F(i, j) is separated into two components:

$$F(i, j) = F_L(i, j) + F_H(i, j)$$

where $F_L(i, j)$ represents the local luminance mean (low-spatial frequency content of the image). The local luminance mean is obtained by averaging the grey values of the image around each point, resulting in a blurred version of the original image. Subtracting this blurred image from the original image, point by point, results in an image containing only the local high-spatial frequencies. $F_H(i, j)$, the local spatial high-frequency content of the image, is amplified by multiplying it by $K[F_L(i, j)] > 1$, a scalar that is a function of the local luminance mean. The final local luminance mean is also modified as a function of the original local luminance mean. The two modified components are then added together to produce the final image. This technique is better than others such as unsharp masking and homomorphic filtering, in that it modifies local contrast as a function of local luminance mean rather than modifying the whole image uniformly. This allows for more contrast enhancement of the bright optic disc area where the masking effect due to media scattering is pronounced. Control of the local luminance mean enables the operator to decide whether the low-frequency content will be maintained over the whole image or extreme brightness changes across the image will be reduced. In addition, the calculation time required for adaptive enhancement is much shorter than that required for homomorphic filtering.

We demonstrated the feasibility of enhancement techniques and their potential clinical value by using fundus photographs of glaucoma patients with cataracts. Photographs were obtained from records of the Glaucoma Service, New England Medical Center.

RESULTS

Case 1 was followed for more than 10 years. A fundus photograph of the right eye of case 1 taken in 1973 shows only slight image degradation due to early precataract lens changes (Fig 1A). In a 1984 photograph (Fig 1B), the image is degraded greatly by a dense cataract. Only major vessels are seen, and the disc is very difficult to evaluate. The results of enhancement of Figure 1B with both homomorphic filtering and adaptive enhancement are shown in Figures 1C and D, respectively. The improved visibility of fundus details in both enhanced images is evident, although the effects of the two techniques differ. The homomorphic-filtered image offers a more natural view of the fundus and makes evaluations of the pallor possible. The adaptive-enhanced image appears more granular with higher con-

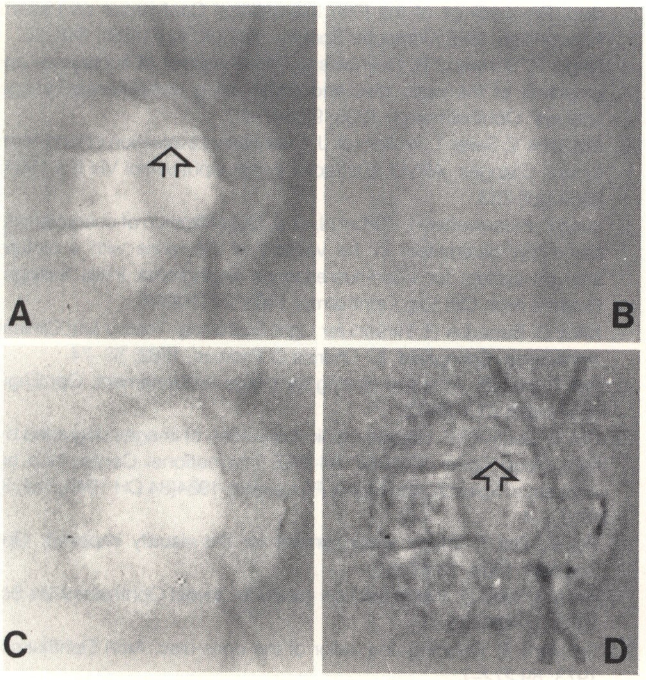


Fig 1. Case 1. Enhancement of disc photograph taken through cataract. **A,** precataract stage in 1973. **B,** 1984 photograph of same disc. Image degraded by cataract. **C,** homomorphic filtering of image in 1B. **D.** adaptive enhancement of image in 1B. Circumlinear vessels (arrows).

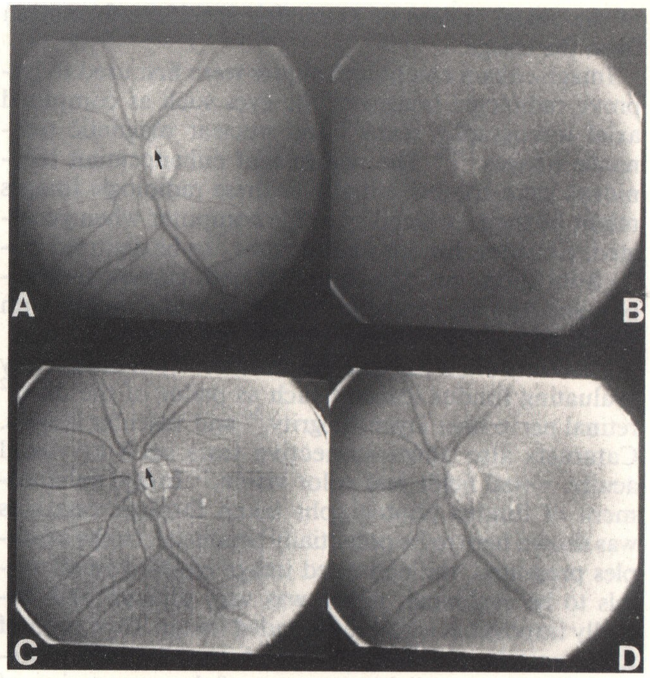
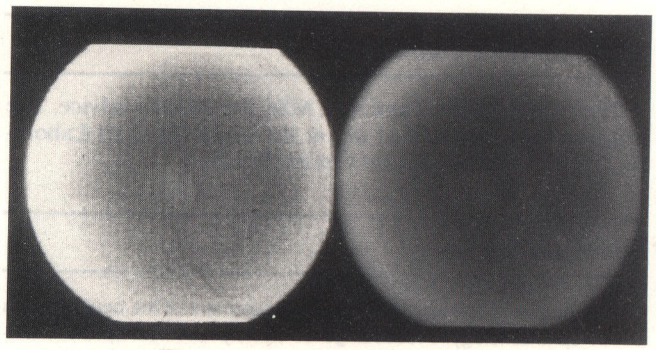


Fig 2. Case 2. Enhancement of photographs taken through cataract. **A,** precataract stage in 1976. **B,** photograph of same eye taken in 1979. Notice degradation of image due to cataract. **C,** enhancement of image in 2B by homomorphic filtering. **D,** adaptive enhancement of image in 2B. Shift in position of circumlinear vessels (arrows) indicates increased cupping.



B A

Fig 3. Case 2. Enhancement of photograph taken through dense cataract **A,** photograph of same eye as in Figure 2, taken in 1981. Denser cataract has severely degraded image. **B,** adaptive enhancement of image in 3A, resulting in improved visibility of fundus details.

trast, but the fine details of the change in pallor seem to be lost with this technique (at least with the set of parameters used for this example). However, in both enhanced images, the two small circumlinear vessels become clearly visible. A comparison of these vessels seen in Figures 1C and D with an earlier version (Fig 1A) shows upward deviation of the superior circumlinear vessel, indicating progression of the cupping.[12] Some small deviation can be noted also in the inferior circumlinear vessel.

Case 2 was also followed for more than a decade. The 1976 photograph (Fig 2A) shows no image degradation. The 1979 image (Fig 2B) is degraded greatly because of cataract formation. Both images were digitized at twice the resolution used for the first case. The results of processing with homomorphic-filtering and adaptive-enhancement techniques are illustrated in Figures 2C and D, respectively. Here too, the improved visibility of the circumlinear vessels demonstrated increased cupping. When the cataracts became denser in case 2 (Fig 3A), enhancement with adaptive filtering improved image quality (Fig 3B) but not enough to offer any meaningful evaluation of the cupping.

DISCUSSION

Research in image processing has expanded greatly during the past few years, encompassing more applications as the size, speed, and cost effectiveness of computers increase.[13] Image processing is used in scientific, biomedical, industrial, and military applications.[13] Digital image processing requires the conversion of continuous images into an equivalent numerical presentation in the computer memory. The computer performs various mathematical operations on the sampled image and then produces a continuous image to be redisplayed. Image enhancement is a subspecialty of image processing. Image enhancement techniques aim to improve the visual appearance of the image. Rather than attempting to represent the original image accurately, these techniques often distort the image, adapting it to properties of the visual system or extracting specific information from the image.

Image-enhancement techniques were first used to improve radiologic images of the eyes such as computed axial tomography scans[14] and nuclear magnetic resonance images.[15,16] The reason that enhancement techniques were applied initially to these radiologic images might be their availability in the computer when generated. However, fundus photographs can be digitized easily from slides into the computer with current technology, and they are available directly as digital images with new fundus-imaging equipment.[17-19]

Cataracts often prevent the clinician from objectively evaluating fundus features such as pallor of the disc,[12] retinal nerve fiber layer integrity,[20] and vascular lesions. Cataracts also affect subjective tests such as visual acuity, visual fields and color vision.[21] Image enhancement of fundus photographs taken through cataracts was shown here to be potentially beneficial. In the examples presented, the enhanced image enabled small vessels to be evaluated, which was very difficult and virtually impossible with the degraded image. Deviation of these vessels indicated increased cupping and represented the only reliable measure of the progression of the disease other than the intraocular pressure. In addition, the homomorphic-enhanced image (Fig 1C) was better than the adaptive-enhanced image in allowing us to evaluate the extent of the pallor. However, the validity of such an evaluation has to be determined.

ACKNOWLEDGMENT

The authors thank Tami Peli, MSc, for valuable advice. The imaging work was carried out at the Image Analysis Laboratory, New England Medical Center, Boston.

REFERENCES

1. Takamoto T, Schwartz B. Stereo measurement of the ocular fundus in ophthalmology. Proceedings of Society of Photo-optical Instrumentation Engineers 361, vol. 3, Biostereometrics. 1982; 324-9.
2. Klein BEK, Magli YL, Richie KA, et al. Quantitation of optic disc cupping. Ophthalmology 1985; 92:1654-6.
3. Nagin PA, Schwartz B. Approaches to image analysis of the optic disc. Proceedings of the Fifth International Conference on Pattern Recognition, IEEE Computer Society. 1980(80 CH 1499); 948-56.
4. Nagin P, Schwartz B, Reynolds G. Measurement of fluorescein angiograms of the optic disc and retina using computerized image analysis. Ophthalmology 1985; 92:547-52.
5. Miszalok V, Seiler T, Wollensak J. Quantitative evaluation of long-term fundus changes. ARVO Abstracts. Invest Ophthalmol Vis Sci 1984; 25(Suppl):253.
6. Jung F, Kiesewetter H, Körber N, et al. Quantification of characteristic blood-flow parameters in the vessels of the retina with a picture analysis system for video-fluorescence angiograms: initial findings. Graefes Arch Clin Exp Ophthalmol 1983; 221:133-6.
7. Miller D, Benedek G. Intraocular Light Scattering: Theory and Clinical Application. Springfield, IL: Charles C Thomas, 1983; 53-74.
8. Peli T, Lim JS. Adaptive filtering for image enhancement. Opt Engineer 1982; 21:108-12.
9. Peli T, Quatieri TF. Homomorphic restoration of images degraded by light cloud cover. ICASSP 84-IEEE International Conference on Acoustics, Speech, and Signal Processing 1984(84 CH 1945); vol. 3, 37.8.1-.4
10. Peli E, Peli T. Image enhancement for the visually impaired. Opt Engineer 1984; 23:47-51.
11. Hess R, Woo G. Vision through cataracts. Invest Ophthalmol Vis Sci 1978; 17:428-35.
12. Schwartz B. Cupping and pallor of the optic disc. Arch Ophthalmol 1973; 89:272-7.
13. Pratt WK. Digital Image Processing. New York: John Wiley & Sons, 1978; V-VI.
14. Millman AL, Gersten M, Lubkin V, Liebeskind A. A volume analysis from CAT scans of the vivo human orbital development. ARVO Abstracts. Invest Ophthalmol Vis Sci 1984; 25(Suppl):175.
15. Seiler T, Wollensak J, Miszolock V. High resolution NMR-tomography of the eye. Invest Ophthalmol Vis Sci 1984; 25(ARVO Suppl):175.
16. Cheng HM, Barnett P, ter Penning B, Aguayo J, Brady TJ, Seddon J, Gonzales G. NMR imaging of ocular pathology. Invest Ophthalmol Vis Sci 1984; 25(ARVO Suppl):175.
17. Warnicki JW, Rehkopf P, Cambier JL, Nelson MR. Development of an imaging system for ophthalmic photography. Biol Photog Assoc 1985; 53:9-17.
18. Cornsweet TH, Hersh S, Humphries JC, Beesmer RJ, Cornsweet DW. Quantification of the shape and color of the optic nerve head. In: Breinin CM, Siegel IM, eds. Advances in Diagnostic Visual Optics. New York: Springer-Verlag, 1983; 141-9.
19. Mainster MA, Timberlake GT, Webb RH, Hughes GW. Scanning laser ophthalmoscopy: clinical applications. Ophthalmology 1982; 89:852-7.
20. Peli E, Hedges TR, Schwartz B. Computerized enhancement of retinal nerve fiber layer. Acta Ophthalmol 1986; 64:113-22.
21. Layden WE. Cataracts and glaucoma. In: Duane TD, ed. Clinical Ophthalmology. Philadelphia: J. B. Lippincott, 1985; vol. 3, Chap. 55.