

## LOW VISION ENHANCEMENT SYSTEM

The Johns Hopkins University, the National Aeronautics and Space Administration, and the Veterans Administration are collaborating to develop and test the Low Vision Enhancement System (LVES), a new technology for aiding persons with severe, chronic visual impairments. The LVES consists of a battery-powered, binocular, head-mounted black-and-white video display equipped with three video cameras. Two cameras provide a 60° normal-magnification binocular view with near-normal disparity to orient the user in space. The center camera supplies a 50° variable-magnification, variable-focus “cyclopean” view to enhance and magnify images. Image-enhancement features currently under development include real-time preemphasis spatial filtering and real-time pixel remapping. Prototypes of the LVES currently are being tested on patients with low vision at the Veterans Administration Blindness Rehabilitation Centers and in its Vision Impairment Center To Optimize Remaining Sight programs.

### INTRODUCTION

Sensory engineering is the science of virtual environments. It is concerned with the rational development of enabling technology for presenting virtual environments that meet the sensory, perceptual, and behavioral requirements of the human user.

One application of virtual environments is sensory enhancement. Data from the physical environment are acquired with physical sensors, transformed, and presented to the user's biological sensors through sensory interfaces such as head-mounted displays. Sensory enhancement depends on the transformation of sensed physical data and the presentation of the transformed data as a virtual environment. It allows a human observer to experience environmental information that he or she could not otherwise perceive.

Because of limitations on biological sensors imposed by disease, abnormal development, or injury, people with sensory impairments cannot experience the range of environmental information readily available to people with normal sensory systems. By understanding the nature and limitations of individual sensory impairments and understanding the nature and bandwidth of information in environmental data, it is feasible to compensate for the impaired sensory system with sensory enhancement technology. For such compensatory sensory enhancement, sensory engineers must understand and characterize normal sensory processing, impaired sensory systems, and the nature of information in environmental data. Compensatory sensory enhancement is then achieved by designing and implementing operations that transform environmental data so as to maximize the fidelity of information transmitted by the impaired sensory system. In this article, we describe an example of sensory enhancement for people with severe visual impairments.

### LOW VISION

An estimated three million Americans suffer chronic, disabling visual impairments that cannot be corrected medically, surgically, or with conventional eyeglasses. The prevalence of these visual impairments, collectively called low vision, increases sharply with age and is expected to double over the next two decades as our population ages.

Current technology to help persons with low vision consists primarily of optical or electronic magnifiers. Optical magnifiers, both microscopes and telescopes, can be hand held, stand mounted, or head mounted. For most such devices, magnification and focal distance are fixed. Electronic magnifiers include closed-circuit television systems, used chiefly for reading, and firmware and software to enlarge text on computer screens. Closed-circuit TV's have the added capability of electronically boosting or reversing contrast, or both.

Besides suffering loss of resolution, persons with low vision experience a loss of contrast sensitivity. This loss reduces visibility of object detail, particularly in faces, and of low-contrast borders such as curbs and steps. Peli and Peli<sup>1</sup> argued that spatial-frequency-selective contrast enhancement could improve the visibility of object detail for persons with low vision. Recently, Peli et al.<sup>2</sup> demonstrated that many persons with low vision can recognize frequency-selective contrast-enhanced images of faces better than unprocessed face images. We have confirmed these findings, but our results show that the optimal parameters for image enhancement vary among individuals.<sup>3</sup>

Loshin and Juday<sup>4</sup> proposed that image remapping might aid persons with central blind spots or losses of peripheral vision. Recent data from our laboratory indicate that persons with central blind spots perceptually

remap visual space in a way that draws the blind spot closed: the brain acts as if the blind spot did not exist. Thus, visual information in the blind spot simply vanishes, and visual distortions are experienced in the region of this “perceptual fold.” These results suggest that an inverse mapping of the image to compensate for the person’s perceptual remapping might restore the missing visual information.<sup>5</sup>

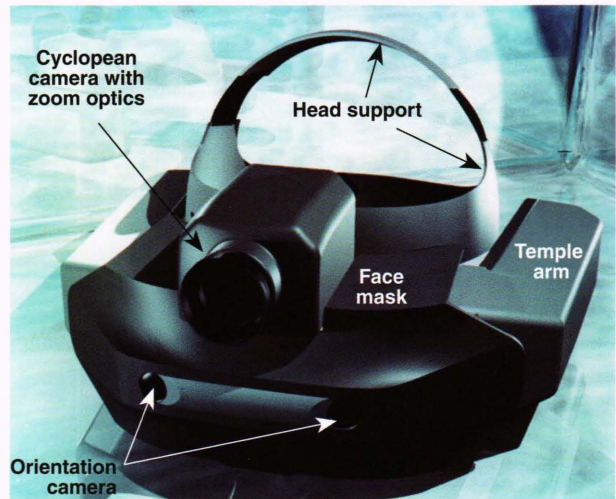
To realize these and other vision-enhancing operations on images for the visually impaired, we developed the Low Vision Enhancement System (LVES).<sup>\*</sup> It consists of a battery-powered, binocular head-mounted video display (video headset) equipped with three video cameras and an external video input (see Fig. 1). User-customized real-time image processing is used to enhance the vision of individual users.

### THE LVES VIDEO HEADSET

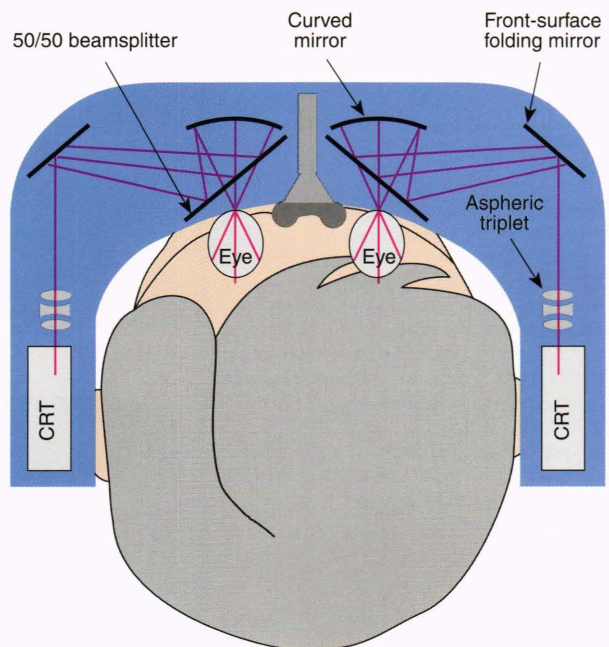
Three video cameras in the video headset provide images to two 8-cm-long, 19-mm-diameter CRT’s positioned along the temples, one for each eye. Figure 2 illustrates schematically how the CRT screens are imaged on the user’s retinas. An achromatic aspheric triplet in each temple arm forms a real, magnified image of each CRT screen. After passing through these lenses, the light from each CRT is reflected off a front-surfaced mirror (also enclosed in each temple arm), which folds the optical path from the side of the head to the front of the eye. A 50/50 beamsplitter in front of each eye directs the CRT rays onto an aspheric curved mirror that is on axis with each of the eyes. The curved mirror images the 8-mm exit pupil of the optical system in the plane of each eye’s pupil and images each CRT screen at optical infinity. Each CRT screen subtends an angle at the retina of 50° horizontal by 40° vertical. Screen resolution is 640 pixels horizontal × 480 pixels vertical, which translates to a nominal resolution of 5 arcmin per pixel (4.7 arcmin horizontal × 5 arcmin vertical).

Two charge-coupled device (CCD) cameras are mounted on the video headset to orient the user in space. One camera produces the right eye image and the other the left eye image. The fixed-focus optics on the cameras generate a 50 × 40° image on each CCD, which results in unit magnification. Binocular overlap in the images is 40° (for near viewing), which produces a 60° binocular field of view (the normal binocular field of view is a little more than 180° with 50° of binocular overlap for straight-ahead viewing). Because the cameras are mounted in front of the eyes, on axis with the eyes’ pupils, binocular disparity in the images is normal. If the user has normal stereopsis, he or she perceives a natural stereoscopic image of the environment.

The central camera on the video headset provides a “cyclopean” view; that is, it shows both eyes the same image. This central camera is equipped with motor-driven 1.5X to 12X zoom magnification and motor-driven variable-focus optics.



**Figure 1.** Artists’ conception of prototype LVES video headset. Adjustable straps support the unit on the head; the temple arms containing the CRT’s and optics are supported by the face mask and can be adjusted for different interpupillary distances. The orientation video cameras, located on axis with the eyes’ pupils, provide a normal-magnification binocular view. The cyclopean camera, mounted on the midline, has zoom magnification optics and variable focus. It tilts down 45° for reading and tasks requiring eye–hand coordination.



**Figure 2.** Schematic of the optics in the video headset, viewed from above. The aspheric triplet lens system forms a magnified intermediate image of each CRT screen. The folding mirror directs the light from the CRT located along the temple to the 50/50 beamsplitter in front of the eye. The curved mirror images the exit pupil of the optical system in the plane of the eye’s pupil and presents a 50 × 40° image of the CRT screen at optical infinity. If the user needs glasses, correcting lenses are inserted between the CRT and the triplet.

<sup>\*</sup>The Johns Hopkins University and Dr. Massof have an equity interest in Visionics Corporation, the exclusive licensee and manufacturer of the LVES.

The user can switch between the orientation cameras and the central camera or can switch to view the image from an external video source, for example, from a videocassette recorder, broadcast receiver, or computer. For the images from the central camera or the external video, the user can switch contrast polarity or enhance the contrast (by contrast stretching, which quantizes intensity levels into fewer bins with greater intensity separations between gray scales).

The electronics for the cameras and CRT's are housed in a belt pack and are powered with rechargeable batteries. Real-time image processing customized for the individual user is added to this basic image-acquisition and display platform.

## REAL-TIME USER-CUSTOMIZED IMAGE PROCESSING

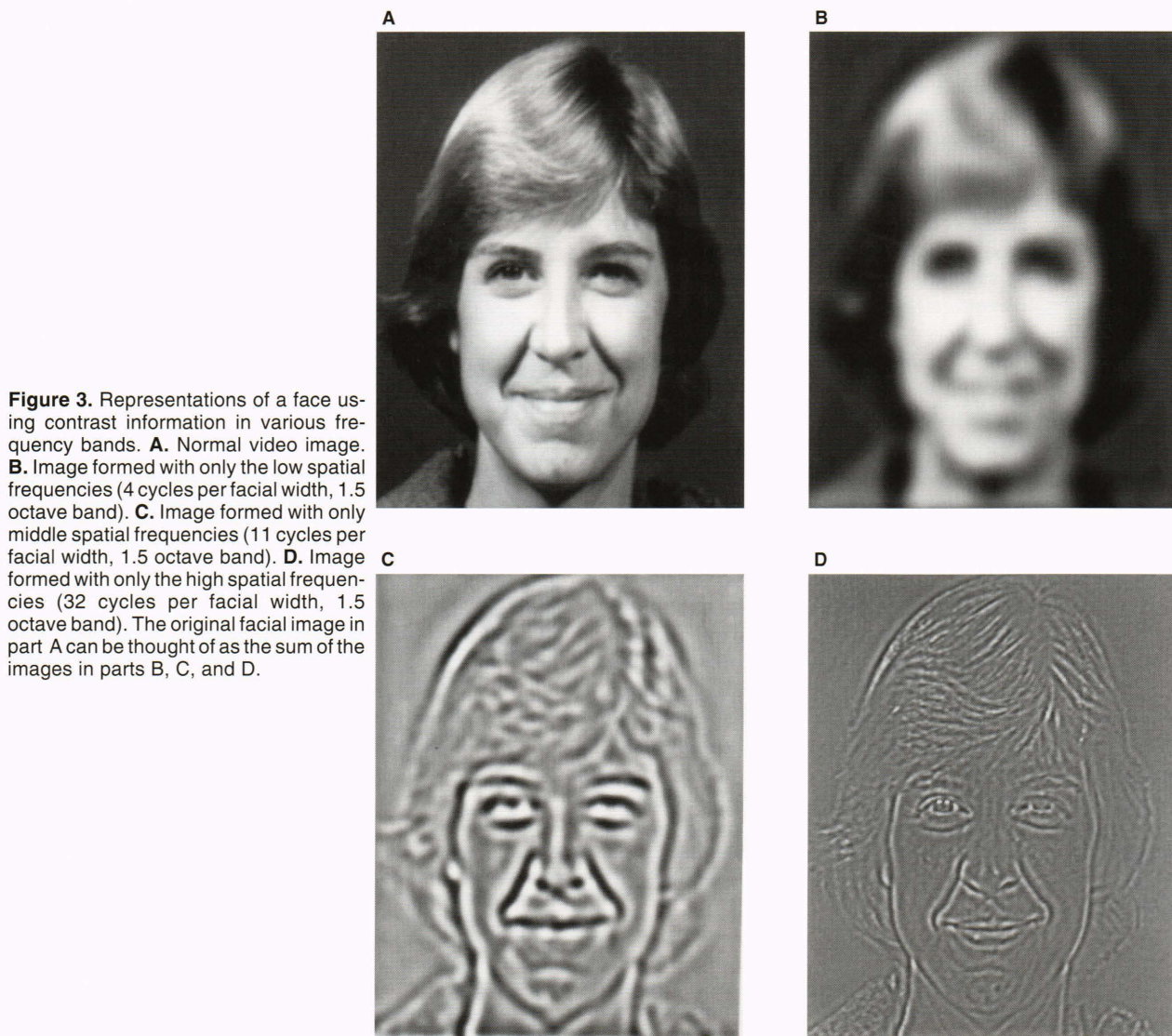
### Contrast Operations

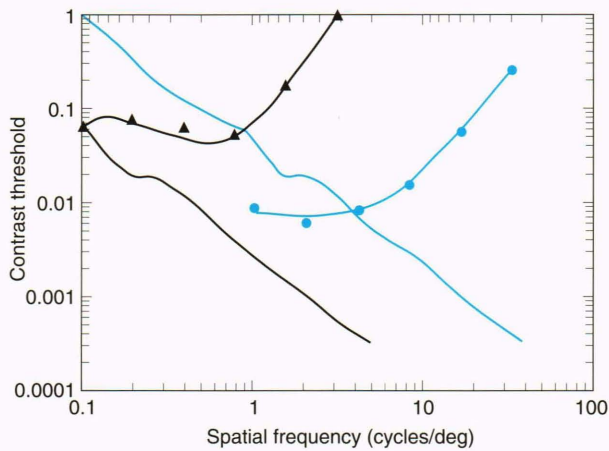
The first vision-enhancing operation to be added to the LVES is real-time spatial-frequency-selective contrast enhancement (active preemphasis filtering). Many indi-

viduals with low vision have great difficulty seeing facial features and recognizing people, including family members and friends. Facial detail is low in contrast, and most people with low vision have a significant loss of contrast sensitivity.

As Figure 3 shows, an image of a face can be represented by contrast information in various spatial-frequency bands. The middle spatial frequencies, relative to the dimensions of the facial image, define the facial features that make a face recognizable. Figure 4 contains a graph of the contrast spectrum for the unfiltered facial image in Figure 3 (average of the two-dimensional spectrum).

Like the modulation transfer function used to characterize an optical system, the human visual system can be characterized with a contrast threshold function. The contrast threshold function is determined by measuring the minimum contrast required to detect a grating with a sinusoidal luminance profile as a function of the spatial frequency of the grating. In Figure 4, a normal-contrast threshold function is plotted along with the contrast spectrum of the facial image. (The inverse of the contrast threshold function, that is, the contrast sensitivity func-





**Figure 4.** Contrast spectra from the face of Figure 3 at 6 m (blue curve) and at 1 m (black curve), and contrast threshold functions for a normal observer (circles) and a low vision observer (triangles).

tion, is equivalent to the modulation transfer function.) Also plotted in Figure 4 is an example of a contrast threshold function for an individual with low vision. The patient's low vision shifts the contrast threshold function, relative to the normal function, up and to the left on the log-log scale. The highest spatial frequency that the patient can resolve at 100% contrast is called the cutoff frequency. The patient cannot see spatial frequencies that exceed the cutoff frequency. The cutoff frequency, which is the limit of visual resolution, corresponds to visual acuity.

Magnifying the facial image to compensate for the patient's loss of resolution shifts the contrast spectrum of the image to the left on the logarithmic scale (black curve in Figure 4) without changing the spectrum's shape. However, because of the patient's higher-than-normal contrast threshold function, the middle spatial-frequency band, which is critical for facial recognition, is below the patient's contrast threshold despite magnification.

To compensate in patients with low vision for the loss of contrast sensitivity at the spatial frequencies critical to facial identification, we use a preemphasis spatial filter. This filter expands the contrast at the middle spatial frequencies, relative to facial dimensions at the appropriate magnification, at the expense of the contrast at low and high spatial frequencies (see Fig. 5).

Using a combination of optical and electronic means, we currently can enhance the contrast of narrow spatial-frequency bands at video rates without delays. This capability can be implemented in an inexpensive, portable, battery-powered device designed for mounting on the LVES video headset. Development and testing of this real-time spatial filter are currently in progress.

### Image Remapping

Patients with age-related macular degeneration and other types of macular diseases suffer blind spots in the center of vision (central scotomas). Patients seem to experience greater visual problems than would be expect-



**Figure 5.** Normal and enhanced video images of a face. **A.** Normal image. **B.** Image enhanced by preemphasis filtering. The original image was filtered to isolate the 11 cycle-per-face-width band, the contrast was increased, and the resulting filtered and enhanced image was added back to the original image.

ed from the acuity loss alone. Such problems are related to the loss of visual information caused by the scotomas' location: the central scotoma forces the patient to use lower-resolution peripheral vision to perform the visual functions usually reserved for high-resolution central vision.

About 50% of the patients we have studied do not perceive their central scotomas.<sup>6</sup> When looking at a grid, they often see distortions in the region of the scotoma, but they do not see a hole in the grid. Our results to date indicate that the brain fills in central scotomas by drawing

the scotoma closed.<sup>5</sup> Figure 6A shows text as a normal person sees it; Figure 6B shows the same text with a central scotoma mapped onto it. Figure 6C shows how the text looks to the patient if the brain draws the scotoma closed, and Figure 6D shows the appropriate compensation for the brain's remapping of the scotoma. The video image compensates for the scotoma's effect by mapping all pixels under the scotoma with a distortion that is the inverse of the distortion caused by the perceptual fold that draws the scotoma closed. Consequently, when the blank area in Figure 6D is registered with the scotoma, the patient sees a complete, undistorted image.

To implement compensating distortions and pixel remapping around blind spots, eye position must be tracked within the video headset. The optics of the video headset make this possible using pupil tracking techniques. Eye position can be recorded at video rates and used to control the region in the image that is remapped.

We currently are able to remap pixels at video rates following eye movements in the laboratory. These operations are performed with parallel processors on a Silicon Graphics imaging computer. The next challenge is to reduce these operations to a system small enough to be carried by the patient.

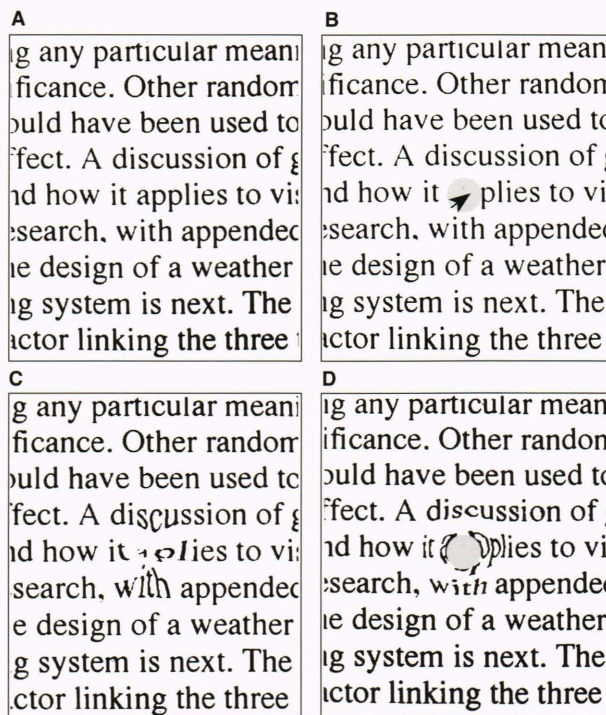
### CLINICAL EVALUATIONS

Prototypes of the LVES video headset are currently undergoing clinical evaluations at the Veterans Administration Blindness Rehabilitation Centers and in its Vision Impairment Center To Optimize Remaining Sight programs in Birmingham, Alabama; Chicago and Hines, Illinois; Kansas City, Missouri; Northport, New York; Palo Alto, California; Tucson, Arizona; and West Haven, Connecticut. Low vision patients participating in the studies live at the medical centers for several weeks during their rehabilitation programs. Reading, daily living activities, mobility, facial recognition, visual-motor performance, comfort, and ease of use are being tested. Also, we are developing prescription, fitting, and training regimens for dispensing and supporting the LVES.

### DISCUSSION

The LVES is an example of sensory engineering applied to vision enhancement. This same technology could be used to enhance normal vision. All of us have low vision under conditions of poor visibility (e.g., haze or fog), at wavelengths outside the visible spectrum (e.g., ultraviolet or infrared), and for image information carried in the polarization state of light. With appropriate sensors and real-time image processing, normal vision could be extended to these other domains.

Future advances in video headset technology will address the issues of size, weight, field of view, color, and resolution. These advances depend on the development of enabling display technology and improved diffractive or other lightweight optics. To increase both resolution and field of view, high-density miniature displays must be developed. Such displays still must meet the requirements of high brightness and high contrast. High-density displays, of course, will require high-speed, high-density drivers.



**Figure 6.** Remapping a video image of text to compensate for a central scotoma. **A.** Unmodified video image. **B.** Scotoma projected onto the word *applies* (see arrow). **C.** What the patient sees in the region of the scotoma, simulated by drawing the scotoma closed. **D.** Remapping of the image under the scotoma to preserve information. The algorithm used to remap the image is the inverse of the algorithm used in part C to draw the scotoma closed.

Much still needs to be learned about the sensory and perceptual sides of vision enhancement. How can new visual information be encoded for our limited bandwidth visual systems? What are the limits and dynamics of visual system adaptation to shortcomings in display and processing technology? What parameters are important to customize the system to the requirements of individual users? These research questions and others are the province of sensory engineering.

### REFERENCES

- 1 Peli, E., and Peli, T., "Image Enhancement for the Visually Impaired," *Opt. Eng.* **23**, 47 (1984).
- 2 Peli, E., Goldstein, R. B., Young, G. M., Trempe, C. L., and Buzney, S. M., "Image Enhancement for the Visually Impaired: Simulations and Experimental Results," *Invest. Ophthalmol. Visual Sci.* **32**, 337 (1991).
- 3 Massof, R. W., and Rubin, G. S., "Face Discrimination with Frequency-Selective Contrast Enhanced Images," in *Vision Science and Its Applications, Tech. Dig. Ser. 2*, Opt. Soc. Am., Wash., D.C., p. 258 (1994).
- 4 Loshin, D., and Juday, R., "The Programmable Remapper: Clinical Applications for Patients with Field Defects," *Optom. Vision Sci.* **3**, 15 (1989).
- 5 Schuchard, R. A., "Perception of Straight Line Objects Across a Scotoma," *Invest. Ophthalmol. Visual Sci. Suppl.* **32**, 816 (1991).
- 6 Schuchard, R.A., "Validity and Interpretation of Amsler Grid Reports," *Arch. Ophthalmol.* **111**, 776 (1993).

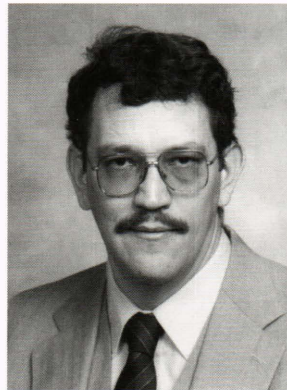
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THE AUTHORS



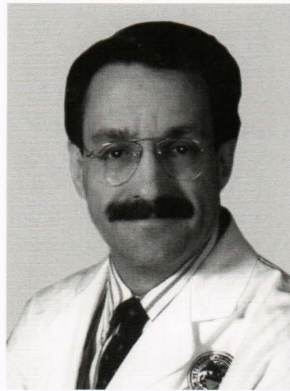
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