6

Rehabilitation

Throughout much of the history of modern audiology the principal rehabilitative weapons have been wearable hearing aids, assistive devices, cochlear implants, and auditory training. Their paths have become interestingly intertwined.

Hearing Aids

Leland Watson, president of the Maico Company, and Thomas Tolan, an otolaryngologist, traced, in their volume, *Hearing Tests and Hearing Instruments*, the early history of the development of the wearable hearing aid. The following is based on their comprehensive review.

Alexander Graham Bell played a significant role in the invention of the first electrical hearing aid. In an effort to help his hearing-impaired wife, he experimented with the electrical properties of carbon granules. Bell failed to succeed with the hearing aid project, but his work with carbon granules led directly to the invention of the telephone. The first viable hearing aid based on carbon granule technology was actually developed by a Viennese physician, Dr. Ferdinand Alt, in 1900. American versions were produced in 1902 by Miller Reese Hutchinson in Mobile, Alabama and C. W. Harper in Boston. Carbon-granule based hearing aids were widely available in the 1920s and 1930s, but they had many problems, not the least of which was fairly poor sound quality. Vacuum tube amplifiers were a giant step forward. The first vacuum tube-based aid in the United States was produced by Art Wengel in 1937. It was called the "Stanleyphone." But it remained for the Aurex company to make the technology widely available. These aids stretched the definition of portable to an extreme degree. They were powered by a separate battery pack. The amplifying unit was mounted somewhere on the upper body, the battery pack either strapped to the midsection or on one leg. How a contemporary woman might outfit herself in the 1930s is illustrated in Figure 6–1.

The truly wearable hearing aid was made possible by the invention, and systematic improvement, of the miniature vacuum tube in the late 1930s. The filaments of the tubes were heated by a 1.5-volt "A" battery, the plate biased by a 22- to 30-volt "B" battery. These aids, about the size of a package of cigarettes, could be worn in a shirt pocket or in a cloth pocket suspended from the neck. They were connected by thin wire to a small transducer, curiously referred to as a "receiver," mounted in the ear canal by a totally occluding earmold. Such aids were made available to the aural rehabilitative

Figure 6–1. How a hearing aid was worn in the 1930s. The amplifying unit, mounted on the chest, was supplied by batteries strapped to one leg, and was connected by a long, flexible wire to the transducer mounted in a fully occluding earmold. (Reprinted from *Hearing and Deafness*, first edition, Murray Hill Books, 1947.)

programs of the various services during and after World War II and were widely distributed to returning servicemen. Examples of these "all-in-one" aids are shown in Figure 6–2.

Sound quality, in these aids, was still marginal. Figure 6–3 shows the frequency response of one such aid at various tone control settings. The wide-band, flat response was still a few years away.

The military programs generated a long-standing debate, which at times became quite contentious, over what might be called the "philosophy of fitting" an aid. On the one hand were the exponents of "hearing aid selection," a procedure promoted most notably by Raymond Carhart and his many students. The rationale here was that the audiologist must seek, through objective testing of speech understanding, the aid that best matches the unique shape and degree of the serviceman's loss. This was achieved by manipulation of gain and tone control of each of several candidate aids in search of optimal word intelligibility. As outcome measures of this approach Carhart adapted, for this purpose, the speech audiometric scores based on the spondee and PB word lists developed at the Harvard Psychoacoustic Laboratory during the war. The underlying assumption of the hearing aid selection procedure was that individuals differed in the unique details of their losses and that the best aid was the aid that complemented the shape of the loss, especially in terms of its frequency response. It was assumed that the speech audiometric scores would order the aids appropriately.

As early as 1946, however, an alternative philosophy emerged from two sources: (1) the British Medical Research Council (MEDRESCO) hearing aid, and (2) the Harvard Report. The MEDRESCO aid was developed by British engineers to meet the needs of the nascent British National Health Service. They were convinced that a single, relatively flat, frequency response was sufficient for most hearing-impaired individuals. Thus, they allowed for only minimal adjustment of the tone control of the aid.

The Harvard Report was generated by a group of scientists, including as noted earlier, Hallowell Davis, working on the National

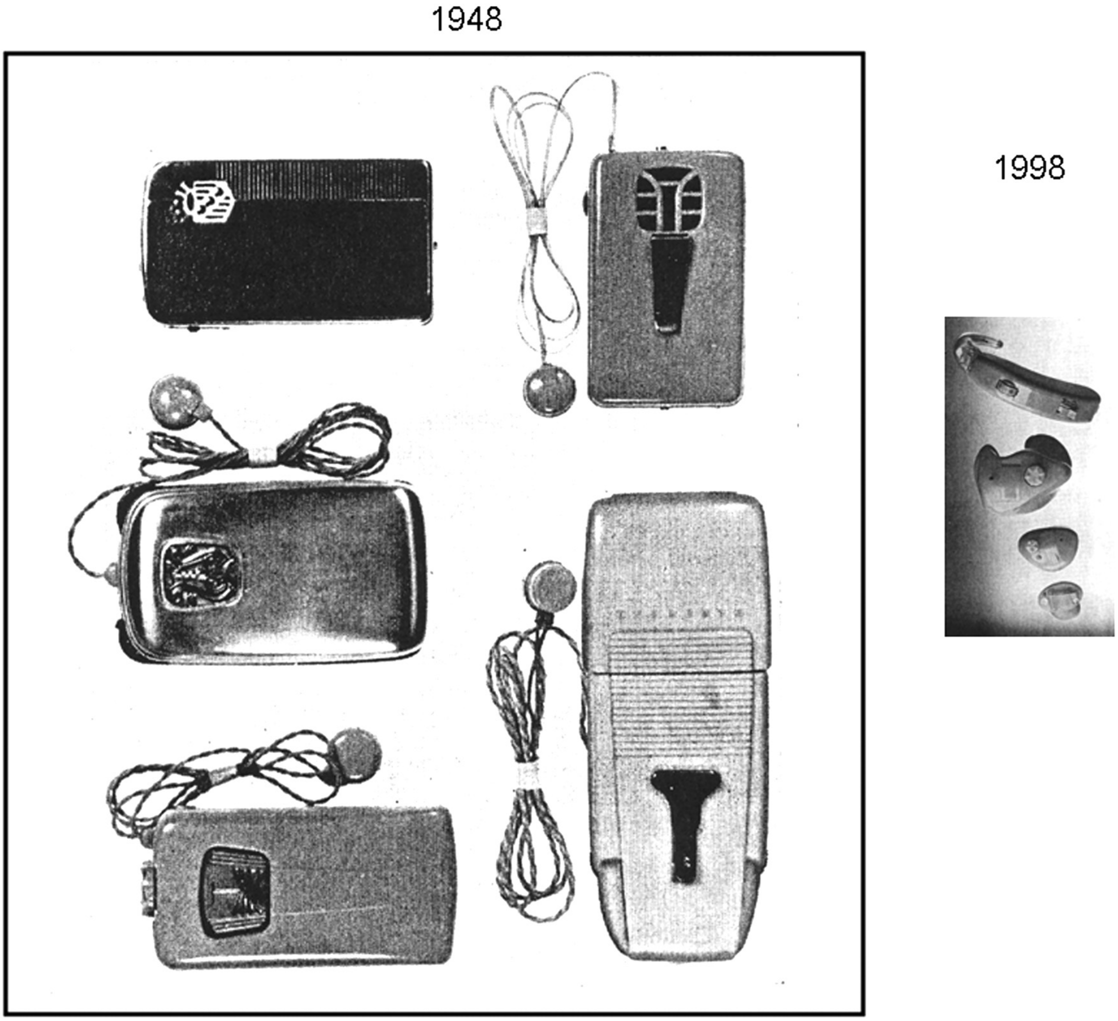

Figure 6–2. Five hearing aids popular in 1948, compared with four hearing aids popular in 1998. Fifty years of miniaturization.

Defense Research Council (NDRC) Aural Rehabilitation Project at Harvard University during the last years of World War II. They tested a number of hearing-impaired individuals with a master hearing aid, in which the frequency response could be manipulated over a wide range. Their report, published in 1946, reinforced the MEDRESCO philosophy in concluding that selective amplification was of little value. A uniform (flat) frequency response, or a response slightly tilted upward in the high frequencies, almost always yielded the best speech understanding scores. Thus, elaborate selection procedures were not warranted. For the next several decades, lively debate ensued between proponents of the two conflicting philosophies. Traditionalists continued to carry out hearing aid selection testing in the Carhart manner while young turks called for reform, but usually to little avail. It must be said, however, that the physical characteristics of the aids of that era

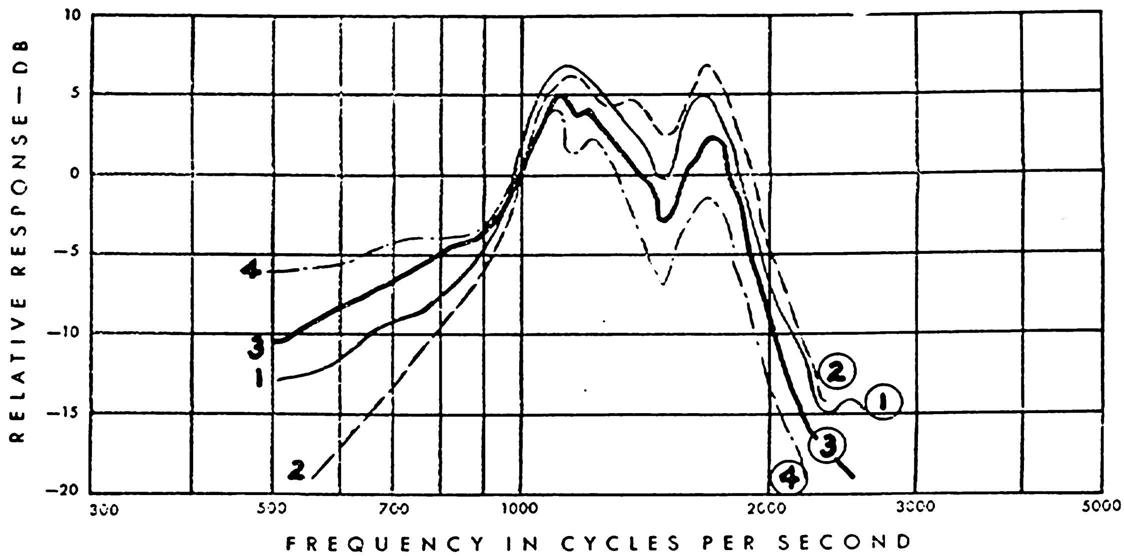

Figure 6–3. The frequency response of an inexpensive hearing aid popular in the 1940s at four positions of the tone control. (Reprinted from *Hearing Tests and Hearing Instruments*, Williams & Wilkins, 1949.)

did not permit very precise control over the frequency response of any aid. In retrospect, it is doubtful that either side could have amassed very much hard evidence in support of its position.

A similar conclusion was reached as early as 1949 by none other than Harvey Fletcher himself. He opined, at the Second Congress of the International Society of Audiology, that the appropriate frequency response of an aid ought to simply mirror the audiometric threshold levels, but that there would be little difference in word recognition scores between such an aid and one with a flat frequency response, so that, for all practical purposes the aid with a flat response should be suitable for everyone. He did concede, however, that if the audiogram sloped downward by more than 20 dB between 500 and 2000 Hz, then the response of the aid should slope upward at about one third the slope of the audiometric contour.

In the early 1950s the transistor was developed and its value in the design of wearable aids was immediately apparent. Transistors were certainly a good deal smaller than miniature vacuum tubes, but the main advantage was the elimination of the need for the bulky, high-voltage "B" battery. Transistors could manage the same amplification powered only by a small 1.5-volt "A" battery. This additional miniaturization made it possible to move the amplifier unit from the chest to a location over and behind the auricle, the behind-the-ear unit, and ultimately into the ear canal itself. Miniaturization also made bilateral fittings feasible, permitting for the first time the capability of exploiting the several advantages of two-eared hearing.

One of the early attempts in this direction was the development of the "eyeglass aid" in the 1960s. In this novel arrangement all of the components of an aid were built into the eyeglass frames, one aid on each side. It was a clever idea, but never really caught on, perhaps because it complicated the process of taking the glasses off and putting them back on. In those days, heavy frames were in vogue, but as that fad passed away, and only thin wire frames remained, there was no longer space for the hearing aids and the era of the eyeglass aid passed away with little fanfare.

An interesting innovation in hearing aid configuration was suggested by Earl Harford (Figure 6–4) and Joseph Barry in 1965. Persons with severe or profound unilateral loss were not considered suitable for hearing aid fitting because of the normal or near normal hearing on the better ear. But these individuals frequently complained of difficulty when the talker was on the side of the poorer hearing ear and difficulty in telling the direction from which a sound was coming. Harford and Barry reasoned that such a person might be helped by a fitting in which the aid and its microphone were mounted on the poorer hearing ear but the signal was actually routed to the better hearing ear. They called this arrangement CROS, standing for "contralateral routing of signal." Several innovative arrangements of the CROS principle were subsequently devised,

Figure 6–4. Earl Harford.

including FM transmission of the signal from one side of the head to the other. In 1966 Harford further suggested that an individual with loss in both ears, but substantially more loss in one ear than the other, might benefit from a BICROS arrangement in which two aids are fitted but both signals are routed to the better ear.

The development of real-ear measurement of hearing aid performance was pioneered by Earl Harford. In the early 1970s, the advent of the miniature Knowles microphone raised the possibility of actually recording the sound pressure level of a signal within the human ear canal. Up to this time, hearing aid performance typically had been measured on a 2-cc coupler. But this approach failed to take into account the variations in response due to differences in real ear canals, transducer placement, and so forth. In 1973, William (Bill) Austin and David Preves of Starkey Laboratories brought samples of the new microphone to Harford's lab at Northwestern University and the trio ran numerous tests, using themselves as subjects, of what we now know as real-ear-measurement techniques. Austin and Preves continued to provide even smaller Knowles mikes as Harford continued his work testing hundreds of patients at the University of Minnesota. The first paper on the subject was presented by Harford at an International Symposium on Sensorineural Hearing Loss in Minneapolis in 1979. His first published paper, entitled "The Use of a Probe Microphone in the Ear Canal for the Measurement of Hearing Aid Performance," appeared a year later in *Ear and Hearing*. By 1985 clinically useful real-ear measurement systems were widely commercially available. In the almost 30 years since the original publications, real-ear measurement of hearing aid performance has become an essential element in the fitting of aids.

In addition to his seminal studies of bone conduction calibration and measurement, and his fundamental studies of speech recognition, the research of Donald Dirks (Figure 6–5), in particular, will be remembered for his development, with Sam Gilman, of a probe tube used to establish the effects of standing waves in the external ear canal over a wide range of frequencies. They were extremely useful in the subsequent development of clinical methods for real-ear measurement via probe microphones.

Figure 6–5. Donald Dirks. (Courtesy of Laraine Mestman.)

Auditory Deprivation and Acclimitization

In 1984 Shlomo Silman (Figure 6–6), Stanley Gelfand, and Carole Silverman published a seminal paper on auditory deprivation. When a person was aided monaurally, the aided ear maintained its speech-understanding capacity over time, whereas the unaided ear gradually declined. The late Stuart Gatehouse, in Scotland, later expanded the concept to include acclimatization, the tendency for the aided ear to improve slightly over time compared to the unaided ear. This important theoretical development has provided strong support for the fitting of aids to both ears whenever possible, even when there is a substantial difference between sensitivity levels on the two ears. It has also alerted researchers to take the initial period of acclimatization into account in hearing aid outcome research.

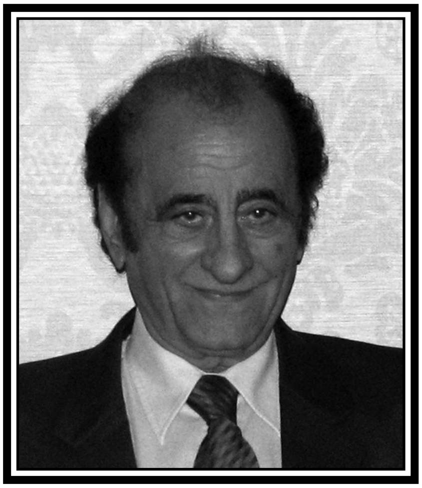

Figure 6–6. Shlomo Silman.

Binaural Aids

The fitting of independent bilateral aids, one to each ear, has had an interesting history. The idea that both ears ought to be aided in order to take advantage of the benefits of two-eared hearing was commonly asserted from the very earliest days of hearing aid fitting. But it was not until the advent of transistors that miniaturization made it practical to mount the aids, and their microphones in or near the two ears. Such fittings were originally called "binaural," but the late Dennis

Bryne of the National Acoustic Laboratory in Sydney, Australia suggested that a more appropriate term would be "bilateral" in recognition of the fact that bilateral aids do not necessarily restore normal binaural function.

In spite of accumulating research evidence that bilateral hearing was, on average, superior to unilateral hearing in persons with normal two-eared hearing, for many years, there was considerable resistance in the marketplace to the fitting of an aid to each ear, probably for two principal reasons: (1) the additional cost of the second aid was a deterrent for many potential users, and (2) conventional speech audiometric test materials seldom reflected, in hearing-impaired individuals, the two-eared advantage so well documented in persons with normal hearing. As this situation improved, with the development of more sensitive tests; however, another problem surfaced. As more and more bilateral aids were fit, especially to elderly persons, it became evident that not all individuals benefited from bilateral fittings to the same degree. Indeed, in some individuals, the presence of the second aid seemed to actually make matters worse. The problem was noted as early as 1939 by Vern Knudsen of UCLA, and by Leland Watson and Thomas Tolan. Watson and Tolan reported that their observations led them to suspect some kind of conflict between the two ears.

The phenomenon of binaural interference, described by Jerger and by Shlomo Silman in the 1980s and 1990s seemed to be at fault. In 2005 the problem was highlighted in a landmark study by Therese Walden and Brian Walden at the Walter Reed Army Medical Center. They showed that some elderly hearing aid users did, indeed, perform better on a test of speech understanding in competition when only one ear was aided. Performance was often poorest when both ears were aided. We still await data on the prevalence of this binaural interference phenomenon in the entire population of hearing-impaired individuals. It is certainly the case that the majority of hearing aid users of all ages perform better with a bilateral fitting, but the lesson for audiologists has been that all potential users, but especially elderly users, must be evaluated under both unilateral and bilateral fitting conditions.

Digital Signal Processing and Microphone Technology

No engineering advance in the past half century has had greater impact on the wearable hearing aid than the advent of digital signal processing in the late 1980s and early 1990s. Now, for the first time, it was possible to actually manipulate the fine grain of the frequency response of an aid in order to match it to the shape of the audiometric contour. This capability, combined with digital compression/expansion and various adaptive algorithms fueled a resurgence in interest in selective amplification. At the same time, studies by David Pascoe and Margo Skinner, at Washington University in St. Louis, by Larry Humes (Figure 6–7) at Indiana University, and by many other investigators, have emphasized the critical impact of the exact degree and configuration of high-frequency sensitivity loss on speech understanding. These two forces have lent such strong support to the philosophy of selective amplification that it has become the virtual rule in hearing aid fitting. Additionally, the laborious testing characterizing Carhart's original concept of hearing aid evaluation have given way to emphasis on fine tuning a smaller number of aids, with heavy reliance on the real-ear measurement of their physical characteristics.

Figure 6–7. Larry Humes. (Courtesy of Indiana University Photo Services.)

Confluent with advances in digital signal processing, microphone technology has advanced to a point permitting the development of a truly directional microphone in which directivity patterns favoring input from a particular direction have been implemented. Although there have been voices of dissent, the available evidence seems to favor the use of directional microphones in most listening situations involving competing speech or noise.

In the months and years to come, it is certain that continuing advances in hearing aid technology will broaden our rehabilitative capabilities. Indeed, we are already seeing aids that learn a client's preferred volume setting, and switch among programs for quiet listening, music, listening to speech alone, and listening to speech in a noisy background. And there are aids that will automatically switch to the directional mode when background noise is detected, aids that can be recharged, and even aids that can be individually programmed to suit a particular lifestyle.

Accountability

As hearing aids and other amplification devices have become more sophisticated, there has been a growing sense that the field stands in need of better outcome measures to assess how well a particular intervention actually helps the hearing-impaired person. For many years, the only outcome measure available was the ubiquitous aided PB score. But Harvey Fletcher's prediction in 1949, that existing word recognition tests were not really capable of differentiating among aids, became ever more evident.

The efficacy of word discrimination testing, as it was then called, was challenged as early as 1960 by Irvin Shore, Robert Bilger, and Ira Hirsh at Central Institute for the Deaf. For the next two decades, there was growing unease about whether PB scores were acceptable as measures of accountability. Finally, in 1983, a study by Brian Walden and his colleagues at Walter Reed reinforced the growing feeling that word discrimination scores were just not up to the task.

Further development took three directions. First, there was a concerted effort to design more sophisticated measures of speech understanding such as the speech perception–in-noise (SPIN) test by Kalikow, Stevens, and Elliott in 1977 and its revised version by Bilger, Nuetzel, Rabinowitz, and Rzeczkowski in 1984, the hearing-in-noise test (HINT) by Nilson, Soli, and Sullivan in 1994, the BKB-speech-in-noise (BKB-SIN) test by Killion et al. in 1997, and its abbreviated version, the QUICKSin test in 2004. New tests will eventually replace the old PB lists, but progress is painfully slow.

A second major development has been the construction of assessment questionnaires such as the Hearing Handicap Inventory for the Elderly (HHIE) by Ira Ventry and Barbara

Weinstein in 1982, the Abbreviated Profile of Hearing Aid Benefit (APHAB) by Robyn Cox and Genevieve Alexander in 1995, the Client-Oriented Scale of Improvement (COSI) by Harvey Dillon in 1997, the Satisfaction with Amplification in Daily Life (SADL) scale by Cox and Alexander in 1999, and the International Outcome Inventory for Hearing Aids (IOI-HA) by Cox and Alexander in 2002. Researcher Robyn Cox (Figure 6–8), at the Memphis Speech and Hearing Center at the University of Memphis, has been one of the foremost supporters of accountability through evidence-based practice in audiology. Craig Newman (Figure 6–9), of the Cleveland Clinic, has been particularly active in the construction and evaluation of questionnaires in a number of areas including hearing handicap in the elderly, tinnitus evaluation, and quantifying hearing aid benefit.

A third development has been the application of cost-benefit analysis to aural intervention by Harvey Abrams and his colleagues at the VA Medical Center in Bay Pines, Florida.

Finally, there is the intriguing development of the concept of acceptable noise level as a predictor of a successful fitting by Anna Nabelek (Figure 6–10) and her colleagues and students at the University of Tennessee-Knoxville.

Many audiologists have made significant contributions to research on hearing aids over the years. Space limitations preclude an exhaustive list, but a sampling of entrants to

Figure 6–8. Robyn Cox. (University of Memphis, courtesy of L. Lissau.)

Figure 6–9. Craig Newman. (Courtesy of the Center for Medical Art and Photography, Cleveland Clinic.)

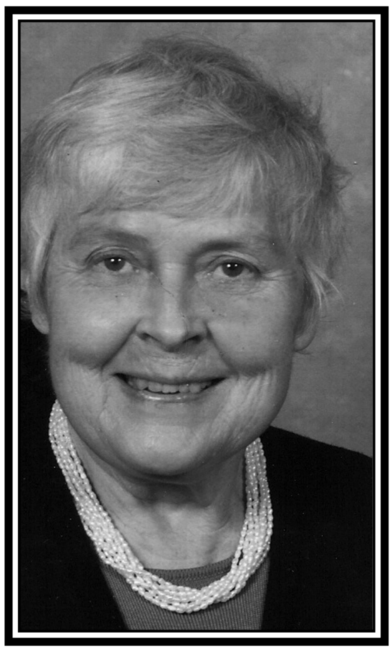

Figure 6–10. Anna Nabelek.

the hearing aid hall of fame would surely include Ruth Bentler, Donald Dirks, David Hawkins, Mead Killion, Sam Lybarger, David Pascoe, David Preves, Todd Ricketts, Margot Skinner, Wayne Staab, Pat Stelmachowicz, Gerald Studebaker, Tom Tillman, Michael Valente, and Laura Wilber.

The Saga of Barry Elpern

No history of audiologists and hearing aids would be complete without an account of the adventures and misadventures of Barry Elpern (Figure 6–11). Barry was an audiologist at the University of Chicago in the 1960s. One cold mid-winter evening in 1967, he was driving home from work on Chicago's south side in the midst of a record-setting midwestern blizzard. Snow and freezing wind swirled around his car as he made his way, slowly and stressfully, along the freeway. But it soon became impassable. After spending the night in his car, he had to walk the rest of the way home in cold, waist-deep snow. He describes a moment of epiphany, during this walk, in which he asked himself, "Is this any way for a reasonable person to live?" As soon as he reached home he instructed his family to pack up as they were moving to Arizona.

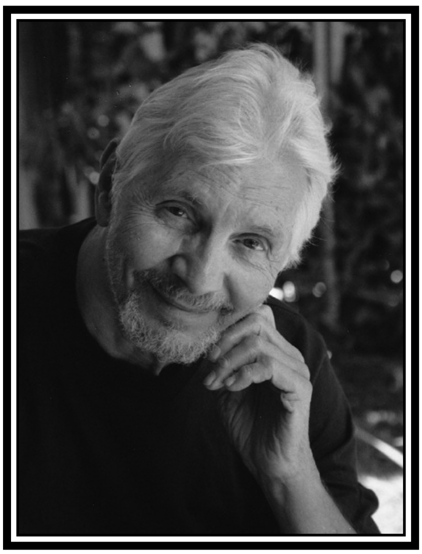

Figure 6–11. Barry Elpern.

In Phoenix, Barry joined a group of engineers who had formed a company to improve hearing aid performance. As part of the operation, they established a dispensary to test-market new products and to assist in corporate cash flow. Because of his audiologic background, Barry was chosen to operate the dispensary. But the American Speech and Hearing Association (ASHA) had long decreed that dispensing hearing aids, by a member, was unethical, and it roundly drummed Barry out of the organization (which in those days was tantamount to ejecting you from the profession). But Barry persisted, and soon other individuals holding a long pent-up concern that ASHA's ethical code was not helpful to the profession began to exert pressure on ASHA to change its ethical stance. It took some time, but in 1979 the ASHA Code of Ethics was finally modified to permit the dispensing of aids.

Nowadays the dispensing of hearing aids and other amplification devices is such a cornerstone of the profession that we have to be reminded of what it was like before the ASHA code was changed. After you had spent hours in audiometric testing and the evaluation of several aids, you could only send the client off to a hearing aid dealer whose code of ethics was less burdensome. It was very unlikely that you would ever see that client again. You never really knew whether they had even acquired an aid or whether they were successful users. There was very little feedback and no accountability. Only in the VA and the military clinics, where the audiologist was permitted to be the dispenser, did the audiologist have any