The Master Hearing Aid

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Abstract

As early as the 1930s the term Master Hearing Aid (MHA) described a device used in the fitting of hearing aids. In their original form, the MHA was a desktop system that allowed for simulated or actual adjustment of hearing aid components that resulted in a changed hearing aid response. Over the years the MHA saw many embodiments and contributed to a number of rationales for the fitting of hearing aids. During these same years, the MHA was viewed by many as an inappropriate means of demonstrating hearing aids; the audio quality of the desktop systems was often superior to the hearing aids themselves. These opinions and the evolution of the MHA have molded the modern perception of hearing aids and the techniques used in the fitting of hearing aids. This article reports on a history of the MHA and its influence on the fitting of hearing aids.

Keywords

hearing aid, master hearing aid, audiology

A hearing aid's effectiveness is no better than its fitting; the most advanced algorithm, signal processor, and transducer complement are wasted if the amplification is not cogent to the patient's needs. Over the decades, deciding what method should be used to establish the best fitting has been an ongoing problem; it remains a matter still imperfectly resolved. Mueller & Picou (2010) report that, ironically, things have changed little in that respect, with 30% of dispensing professionals using objective verification in the majority of fittings. Today, as it was in the past, the most usual and customary way to confirm suitability of a hearing aid fitting in the (adult) patient is to ask, "How does it sound?" (Studebaker, 1982).

One could ask why greater progress has not been made in sorting out this issue. This article discusses some of the factors that have contributed to this dilemma. An examination of the evolution and influence of the master hearing aid (MHA) historically informs our understanding of the many fitting strategies and systems used for prescribing amplification and suggests reasons for both their failures and successes. The reader will become aware of the interdependent relationship that exists between current and past fitting practices and the use of fitting devices.

In the 1920s to the 1950s, MHAs were used to select the component parts of the hearing aid so that the instrument could be properly assembled. At the same time, providing a listening experience that in theory could be duplicated in the fitted instrument grew in importance. Although the nature of fitting modern digital hearing instruments has changed significantly by comparison, the necessity for instrumentation intended to assist fitting remains. Apropos, when today's professional uses a computer with associated prescriptive

software to fit a patient, the fitting and follow-up is being accomplished with a modern version of the MHA.

The enduring presence of the MHA is an unrecognized part of hearing aid history. The audiological literature has given short shrift to the MHA's relationship to hearing aid fitting—a few easily overlooked chapters in audiology texts (Berger, 1975; Franks, 1978) and a limited number of research articles. However, early and contemporary otological and hearing aid literature reveals that a preponderance of the hearing aids fitted over the past century usually involved the use of MHAs or similar fitting devices. Audiologists are aware that the comparative fitting methodology implemented in audiological clinics until the 1980s did not involve MHAs (Carhart, 1946a, 1946b, 1946c, 1950, 1959). Nevertheless, the actual hands-on fitting of the aid and especially follow-up adjustments were implemented by dealers, who, more often than not, relied on an MHA (see section: The Hearing Aid Dealer and MHAs).

We've chosen to use the term Master Hearing Aid to describe the broad array of assistive devices, machines, and instruments that have been invented or developed over the decades in the United States to properly accommodate amplification to an individual's unique hearing requirements. Berger (1975) suggested that Hayden (1938a) may have been the first to use the term in an article about an early MHA, the *Audioscope* (discussed below). The term has been used in

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Figure 1. Left: The 1937 Sonotone Audioscope, capable of connecting more than 280 different combinations of carbon type transmitters (microphones), boosters (amplifiers), and receivers to find the best sounding arrangement.

Note. Fitting consisted of trial and error hookups until a satisfactory listening arrangement was found. The No. 13 in the illustration shows the optional receivers available and No. 2 shows the transmitters (microphones) that could be exchanged as desired. Right: The illustration depicts testing with a later, binaural, version of the Audioscope.

various ways since, not always favorably, but in a general sense, it describes rather well the many alternative versions that have surfaced since the introduction of the electrical hearing aid.

Figures 1, 2, and 3 show examples of MHAs from early to more recent times. The design and function of each succeeding version reflected the state-of-the-art of its era, adapting appropriately as technologies and fitting schemes evolved.

The Nature of the Problem

The problem of how-to-fit was recognized by the early pioneers in hearing aid development. In their search for an answer, they turned naturally to inventing “fitting machines,” for their backgrounds were in engineering and manufacturing. The notion of using a specifically designed mechanical or electrical apparatus to execute a corrective prescription for a sensory deficit is not novel. An obvious example is the use of the *phoropter*, an effective adjunct in the field of visual correction. The phoropter calculates the correct lens prescription according to the patient’s responses as lenses are being compared. The *autorefractor* is an automated expression of the phoropter, a computer controlled device that provides an objective account of refractive error without the need for patient input.

However, with regard to compensating for hearing loss, there is one significant difference. Franks (1978), in commenting on the contrast between the instrumentation used by the optometrist in fitting eyeglasses and master hearing aids used by hearing aid professionals in the past, makes a telling observation:

Figure 2. The Beltone Selectometer, introduced in 1947, very probably the first MHA to be used for fitting vacuum tube hearing aids.

Note. The Selectometer was designed to demonstrate the Monopac hearing aid (discussed in the text), a revolutionary hearing aid for the times. (Also see Figure 10.)

The optometrist is trying to prosthetically remedy a conductive problem, light transmission through the lens of the eye, and would never attempt to use a device . . . to attempt to remedy a receptor problem such as deterioration of the retinal structure. The audiologist is trying to prosthetically remedy a receptor problem, deterioration of the cochlear mechanisms . . . (p. 85)

Figure 3. The Precision Acoustics SAT-2 MHA from the late 1970s, a representative example of the type of master hearing aid developed for fitting transistorized hearing aids.
Note. This instrument featured a pure tone audiometer, masking, speech testing, and the choice of several optional receivers.

The diminished transmission of the acoustic signal through the impaired middle ear is equivalent to the diminished transmission of visual stimuli through the defective lens and is relatively easily resolved with amplification. By contrast, dealing with cochlear and neural dysfunction is an altogether different proposition involving, as it does, a sensory system in functional and operational disarray. Therein lies the conundrum faced by hearing professionals: prescribing the performance of an externally worn artificial device to restore or remedy the disordered and ambiguous behavior of a damaged auditory nervous system (Plomp, 1978). It is no wonder that the whirlwind of methods, devices, procedures, and suggestions of the past for prescribing or selecting appropriate amplification have met with either total or partial failure. Given the nature of the obstacles, it is a small miracle that we have been able to develop today's relatively useful approach to fitting. It is not unreasonable to suggest, based on the evidence, that progress in fitting has been immeasurably advanced because of instrumentation specifically designed for assisting fitting: the MHA.

Fitting by Substitution

Recall that early electric hearing aids were large carbon type devices employing telephone components; the very earliest were table mounted. Subsequently, wearable versions having three separate parts appeared; the different pieces were connected by cords and worn on different parts of the body (see Figures 4 and 5). Carbon aid microphone/transmitters had

Figure 4. The early carbon-era hearing aids typically consisted of three parts, the transmitter (microphone), the receiver, and, when required, a battery.

Note. The picture shows an early 1900s' hearing aid with the transmitter at chest level and the receiver (earphone) held to the ear. The battery is concealed in the model's purse.

two thin metal plates with pressure sensitive carbon particles packed in between. When acoustic waveforms impinged on the outward facing more flexible plate, its movement caused corresponding movements in the granules, causing proportional changes in electrical resistance. These electrical variations were amplified and changed to acoustic signals by magnetic earphones (receivers).

Three years after inventing the first practical wearable electric (carbon) hearing aid in 1902 (Watson & Tolan, 1949), Miller Reese Hutchison patented an MHA device (Hutchison, 1905). Nine receivers and 12 microphones having "graduated predetermined values," were to be systematically interchanged until a "satisfactory improvement in hearing" was determined. The primary focus of the patent was the method of "fitting" he described, that is, the exchanging of components. Remarkably, he also described testing hearing with tones and whistles, as well as a method for standardizing "articulation" testing by using a "talking machine" such as a gramophone.

The transmitters (microphones), earphones, (and the filters and booster units) of the time could be manufactured with different resonant peaks and connected to each other to produce a useful additive frequency-gain response. Kranz (1928) characterized this in a hearing aid patent wherein components, each with different natural frequencies, were combined to accentuate "the frequencies to which the person hard of hearing is less sensitive" (p. 2). In sum, hearing aid

Figure 5. A typical carbon hearing aid from the late 1920s.

Note. In this picture, the receiver (earphone) is connected to a headband, and a frequency response switch is provided for accenting the highs or lows. The change in response was ordinarily quite restricted.

fitting consisted of alternately exchanging different transmitters, earphones, acoustic filters, and batteries until satisfaction was reached. (Curry, 1953; Davis & Silverman, 1960, p. 324; Duggan, 1949; Fowler, 1943a; Hayden, 1938a; Lybarger, 1938; Watson & Tolan, 1949, p. 288). In time, searching for appropriate amplification properties by substituting and combining components became the standard fitting procedure; we refer to it as the “substitution method.” In 1944, Leland Watson (who founded the Maico Company in 1936), in an article in the *Laryngoscope*, affirmed the substitution method, the interchanging of receivers and microphones combined with the use of rudimentary tone controls, as a desirable fitting strategy for vacuum tube aids (discussed later; Watson, 1944). This strategy lasted until the introduction of transistorized hearing aids.

The State of the Art, 1930s-1940s

The Medical/Clinical Setting

Up until the early 1940s, the measurement of hearing in the doctor’s office was usually determined by tuning forks and voice and whisper tests at given distances (Bunch, 1943; Davis & Silverman, 1960, p. 143; Saltzman, 1949, pp. 142-151). ENT practitioners were slow to accept the audiometer despite articles encouraging its use (e.g., Hunter, 1938; Jones & Knudsen, 1938; Wells, 1938). In 1937, less than 10% of otologists used an audiometer, rising to 80% by 1947 (Watson & Tolan, p. 23). Otologists could differentiate between sensorineural and conductive pathology using tuning forks but, without audiometry, were unable to determine reliable thresholds (Hirsh, 1952, p. 282). In the late 1930s, audiometric zero reference levels were still being sorted out, and various audiogram forms were in use (Watson & Tolan, 1949).

It is interesting to note that speech audiometers as we conceive of them were not in existence in the 1930s. A few clinics or otologists may have had custom-built amplifying equipment but most practitioners did not (Watson & Tolan, p. 433); well documented, calibrated speech test recordings did not become widely available until the late 1940s (Benson et al., 1951; Hudgins, Hawkins, Karlin, & Stevens, 1947). The usual procedure for speech tests involved presentation by live voice in quiet surroundings at specified distances from the patient, who covered the untested ear, sometimes just by pressing down on the tragus. The speaker moderated his voice level from whisper to very loud, depending on the purpose of the test, either as an aid to diagnosis or to determine the most suitable hearing aid combination (Carter, 1943; Davis & Silverman, 1960, pp. 338-339; Jones & Knudsen, 1938; Newhart & Hartig, 1939; Saltzman, 1949). Rules of thumb related the degree of hearing loss to the distance between talker and patient as voice intensity was varied (Hirsh, 1952, pp. 144, 269; Saltzman, 1949). Fowler (1943b) writing on the usefulness of the pure tone audiometer, was understandably critical of this speech testing methodology, pointing out, “It is physically impossible to maintain one’s soft or loud voices at a given level of intensity . . . because the voice automatically changes in loudness with distance from the patient . . .” (p. 58).

Reading the early otological literature, it is clear that many otologists found it difficult and too time-consuming to deal with hearing aid amplification (Jones & Knudsen, 1938; Watson & Tolan, 1949, pp. 433-435). The average ENT practitioner had neither an active nor informed interest in hearing aids (Fletcher, 1932; Jones & Knudsen, 1938; MacFarlane, 1944). In the words of Day (1940; quoted in Watson & Tolan, 1949),

. . . many an otologist loses interest in the management of his hard of hearing patients when he finds they are not amenable to [medical or surgical] treatment, and dismisses them with the suggestion that they try out some hearing aids. This is comparable to an ophthalmologist telling a patient with defective vision to try out some glasses. (p. 434)

Even when relatively reliable pure tone threshold measurements became more available, authorities were unclear how this information should be used to calculate appropriate amplification (Weille & Billings, 1937; see also Bunch, 1943, pp. 113-117). A few manufacturers began to issue fitting guidance based on audiometric thresholds (e.g., Hayden, 1938b; Kranz & Rudiger, 1942; Lybarger, 1944a, 1944b). But these were essentially guesswork on the part of the manufacturer although those of Radioear proved to be prescient in their later applicability (discussed later).

Hayden (1938a), one of the otologists then writing about amplification, offered a quite clever but very involved procedure that used pure tone threshold information as a basis for fitting:

By passing the audiometer's calibrated tones [after fastening the earphone by means of a tight-fitting cushion] . . . to the hearing aid transmitter [microphone], and measuring the output with a decibel meter, the overall "tone characteristics" of the various arrangements of component parts can be plotted into "response curves" of the hearing aid. The actual change the hearing aid makes in the patient's hearing can be ascertained by attaching the audiometer's earpiece to the transmitter of the patient's hearing aid and charting the audiometer reading of the patient in the usual way . . . when plotted on the patient's original audiogram, a graphic picture of the hearing before and after fitting is immediately exhibited . . . (p. 724)

Obviously, Hayden's proposed fitting method was fraught with procedural and reliability issues but is representative of early attempts to quantify the relationship between audiometric thresholds and frequency-gain response shaping.

Many believed relying solely on pure tone threshold values was ineffective as a means for specifying desirable amplification parameters (e.g., Braly, Utley, & Harris, 1938; Myers, 1938). Arthur Wengel, credited with inventing the first wearable vacuum tube aid in the United States in 1937 (Watson & Tolan, 1949; Wengel, 1940a), discussed this in his patent application for an MHA: ". . . the threshold audibility curve determined in a laboratory under sound insulated conditions is of little value in designing a hearing aid device" (p. 1). He described an MHA that enabled measurements within the residual auditory area using both pure tones and a broadband noise with "substantially uniform frequency distribution" across the spectrum. Listening to the noise stimulus at a predetermined level in a sound field, the patient signaled when pure tones at different frequencies became audible as they were increased in intensity. The inverse of the just audible thresholds constituted the "frequency-amplification curve of the amplifier" of the hearing aid (Wengel, 1940b).

Earlier Balbi (1935) had proposed a fitting scheme based on bisecting the residual auditory area. The response of the hearing aid was determined by filtering the hearing aid's output to match the curve that was calculated by determining the midway points, across frequency, between the threshold of "minimum audibility" and the "pain" threshold. Balbi did not specify the procedures to be used for obtaining the two threshold measures.

Watson & Knudsen (1940), foreshadowing fitting procedures that were proposed decades later (e.g., Miller, Niemoeller, Pascoe, & Skinner, 1980; Pascoe, 1978; Shapiro, 1976; Victoreen, 1973), devised an intricate method of fitting based on obtaining most comfortable levels for pure tones. The frequency-gain curve of the prescribed aid was calculated by a formula that compared the patient's most comfortable loudness levels (MCL) across frequency to the MCLs for normal hearing individuals. Following this, using an MHA, the various components of the hearing aid were chosen that matched the prescribed curve.

In fact, most of the proposed procedures that involved pure tone stimuli as part of the fitting strategy relied on the MHA to subsequently assemble the components necessary to match the prescribed performance. For example, Strommen (1946) received a patent, assigned to Acousticon, for an MHA that used pure tones to obtain the patient's unaided thresholds in test environments where background noise was not controlled. The tester then selected, using his best judgment, a combination of components that was felt to bring the patient's threshold back to "normal" (not defined). Successive combinations were substituted as needed until the "best improvement [was] provided thereby over . . . unaided hearing."

Hayden (1938b) also described another procedure where pure tone thresholds, an MHA and speech testing were all linked to select the best aid. The method involved a series of translucent overlays provided by the Sonotone Company, each containing both a printed threshold configuration and a recommended hearing aid frequency-gain response shape for the thresholds depicted. After matching the patient's threshold configuration to the appropriate overlay, the otologist used the Sonotone MHA (*Audioscope*; see Figure 1) to assemble the components that would match the frequency-gain curve shown on the overlay. Speech testing, such as it was, followed to substantiate the fitting.

The Retail Community

During the first fifty years of electric hearing aids, the profession of audiology did not exist. It was the hearing aid dealer alone who fitted and sold nearly every hearing aid. Dealers were relatively few in number, estimated in the United States at approximately 3,000 during the 1940s in a population of about 130 million (Skafte, 1990). Any training a dealer received was from the company whose products he sold, or was learned on-the-job (Watson & Tolan, 1949, p. 432). An estimated 50,000 hearing aids were in use in 1936 (Watson & Tolan, 1949, p. 435), and Hayden (1938b) estimated that in 1938, approximately 90% of the aids in use were of the carbon type. Annual sales grew by 1943 to somewhere more than 100,000 units (Berger, 1984, p. 92; Watson & Tolan, p. 423).

There was little understanding at the retail level of the technical specifications of available products, except in the crudest sense, and no access by dealers or other hearing professionals to hearing aid measurement instrumentation (Lybarger & Lybarger, 2000; Watson & Tolan, 1949, p. 408). Even if available, the technical descriptions of hearing aid performance by themselves were of little help in fitting. Quality control, especially of carbon hearing aids, was minimal and inconsistent, and the performance and specifications of instruments from one company could hardly be compared to another (Berger, 1984; Hirsh, 1952, p. 78). It was not until 1961 that the industry agreed on a standardized method of measuring hearing aid performance (Berger, 1984; Lybarger,

1961), and not until the 1980s that equipment for measuring performance became widely available.

Summing Up

The early fitting strategies and proposals reviewed above clearly illustrate how difficult it was for hearing professionals of the time, both otologists and dealers, to cope with the variables of hearing aid gain and output, pure tone thresholds, suprathreshold measurements and their relationship to the most desirable frequency-gain response. Without the MHA, if one wished to fit a hearing aid, the procedure amounted to little more than using trial and error to choose between components (Balbi, 1935). By comparison, the MHA provided an efficient, and relatively orderly way to combine and assemble hearing aid components to discover an acceptable fitting.

Goodness of Fit

An overarching issue from the beginning of hearing aid fitting to the present has been defining the criteria/evidence required to guarantee “goodness of fit.” In spite of advances in instrumentation and fitting procedures over the years, it is apparent that valid and reliable metrics have not yet been developed. This deficiency speaks directly to the inherent difficulty in establishing an objective criterion of goodness of fit.

An examination of the basic methods used with MHAs (and in general) over the decades shows three common approaches: (a) selection of the best aid based on speech testing results, (b) using threshold results, or suprathreshold loudness judgments to prescribe or calculate a fitting, and (c) determination of adequacy based on subjective judgments by the patient. Not mutually exclusive, in most instances more than one has been involved in substantiating acceptable performance.

Speech Testing

Following Fletcher and Steinberg’s investigations on the intelligibility of speech (Fletcher, 1929; Fletcher & Steinberg, 1929) speech testing in one of its various forms became an early and popular measure of “goodness of fit.” For example, Braly (1938) maintained that “speech tests effectively demonstrate the relative merits of different hearing aids” (p. 778). Berry (1939) describes the use of a nonsense syllable test developed by Robert West, the director of the first speech and hearing clinic at the University of Wisconsin, where the hearing aid with which the patient received the best score was selected. Carhart (1946a) suggested that one aid could be differentiated from another if the word recognition score of one was 8% better than the other. Davis et al. (1946) declared that the primary objective of hearing aid evaluations was the “intelligibility of speech” using word tests.

As pointed out earlier, speech testing from the 1930s into the early 1940s usually consisted of live voice delivery with the talker varying both voice level and distance from the patient although during and especially after World War II sound-field comparative evaluations became the normative procedure in military hospitals and audiology clinics. Still, at the retail level, most customers were and continued to be tested and fitted in homes or in satellite offices where background noise was uncontrolled (Skaft, 1990; Strommen, 1946). When testing with an MHA, unmonitored live voice word tests and/or cold running speech were commonly used to find the best combination of components. Kranz & Rudiger (1942), describing retail fitting procedures, said, “Final check of the effectiveness of the hearing aid is made on the basis of articulation tests, and [calculating] the distance range of satisfactory hearing . . .”

It took the passage of years to realize how very fragile word recognition scores could be, and how unreliable were the methods that used speech test scores as criteria for selection, even when environmental and methodological variables were closely controlled. Differences in talkers, speech materials, list length, level of presentation, bandwidth, transducers, fatigue, and competing signals are a few of the factors that produce different speech recognition scores. (Chial & Hayes, 1974; Olsen & Matkin, 1991; Schwartz, 1982; Studebaker, 1982). It is obvious that speech intelligibility testing in the early years was an inadequate method for verifying goodness of fit, but it had face validity and offered a convenient means for demonstrating the benefits of amplification and for judging the usefulness of alternative combinations.

Pure Tone Thresholds and/or Suprathreshold Loudness Judgments as Criteria

Earlier, we described some of the unwieldy proposals for hearing aid fitting involving pure tone threshold measurements. As usage of audiometers increased, it became customary to arrange the hearing aid’s components to approximate the configuration of the patient’s audiometric thresholds. That is, increased amplification was located where hearing loss was greatest, and vice versa. This method, generally referred to as “selective amplification,” was an integral part of most early hearing aid fitting schemes (Holmgren, 1939; Jones & Knudsen, 1938; Pascoe, 1978; Tumarkin, 1935; Watson & Knudsen, 1940) until an influential document called the Harvard Report appeared in 1947 that recommended fitting all patients with a flat or slightly rising frequency-gain curve irrespective of threshold shape (Davis et al., 1947). The Harvard Report had an unsettling effect on hearing aid fitting at the time, for as Lybarger (1978) said, selective amplification “. . . has always been a preliminary . . . [step] in hearing aid evaluation . . .” (p. 263). The issue was finally resolved decades later but not without some controversy (discussed in a subsequent section: Research Using MHAs).

The first author once wrote articles (Curran, 1972, 1974) suggesting that prescribing frequency-gain curves using threshold-based formulas was a futile undertaking. The intention was to elevate the use of the MHAs of the day for fitting as opposed to relying on prescriptive formulas, for the latter were then in their formative stages and relatively primitive. Looking back, it is apparent that the assumptions made for those articles were mistaken. Modern threshold derived prescriptive algorithms are vastly more elegant than the early initiatives. Today, the combination of personal computer and prescriptive formulas allows even the most inexperienced hearing professional to provide an initial fitting that approximates a targeted in situ hearing aid response. Whether or not the targeted response aims to maximize acceptance of amplification or a patient's speech recognition remains a decision that is made by that professional.

Watson & Knudsen (1940) recommended suprathreshold loudness measures as a method for determining frequency-gain curves. Despite extensive research in following decades advocating the use of loudness estimation as a fitting procedure (e.g., Allen, Hall, & Jeng, 1990; Gabriel, 2002; Geller & Margolis, 1984; Kiessling, Schubert, & Archut, 1996; Shapiro, 1976; Valente & Van Vliet, 1997; Victoreen, 1973; Welch, 1988), few manufacturers have succeeded in devising a user-friendly, time-efficient MHA using loudness estimation. Numerous issues have been identified that make suprathreshold measurements less practical in MHAs; differences in instruction, stimuli, and procedures may be expected to result in different outcomes; test-retest reliability is problematic and, additionally, threshold measures by comparison are quicker and more convenient (Beattie, 1982; Davis et al., 1946; Dillon, 2001; Eberling, 1999; Humes & Halling, 1994; Sammeth, Birman, & Hecox, 1989).

Patient Reports as Criteria

The third method used with MHAs, both in the past and today, has been to rely on the patient's subjective judgments of benefit and acceptability of the amplified signal. In their classic article, Watson and Knudsen (1940), in an attempt to develop a more systematic procedure for fitting, remarked that one should not "rely on the subjective impression of the patient in selecting [a] correct response, as he/she has not heard the lost sounds for a long time" (p. 408). Braly (1938) suggested that the new patient may select the better sounding aid, but it very probably would result in reduced word recognition scores. Norman Watson, quoted in Watson and Tolan (1949, p. 389) said, "Selection by personal preference is one of the poorest methods of all."

Despite these proscriptions, however, relying on qualitative judgments by the user was standard practice in the field. For example, in the description of an early MHA, the Beltone *Selectometer* (see Figure 2), it was stated,

An individual whose hearing correction is being tested *recognizes* [emphasis added] the right combination [of hearing aid components] to fit his needs. This exact combination is his "fitting diagnosis" and his hearing aid will fit it exactly. (Seibel, 1949b, p. 21)

We accept the essential validity of the early cautionary observations but also realize that even today most hearing aids are still being routinely fitted and/or adjusted on the basis of the patient's subjective impression. Very little has changed over the years despite the information and guidance the computer-based MHA provides. Ultimately, subjective reports from the adult patient both during and after the fitting will probably remain a critical part of hearing aid fitting.

The First Successful MHA

In 1935 the Radioear Company introduced the Selex-A-Phone, an MHA based on and designed to facilitate the substitution method ("His Hobby," 1949; Myers, 1938). It is commonly assumed this was the first realistic, commercially available MHA (Berger, 1975; Franks, 1978). Consisting of three (later four) carbon microphones, a number of booster (amplifier) circuits with different amplifying properties, and "any number" of air and bone conduction receivers, it afforded 135 possible fitting combinations (see Figure 6). Of significance was that it enabled the tester to rapidly switch between different component hookups to provide immediate comparisons between successive listening conditions. In addition, their literature claimed "made-to-order hearing aids," for the results of the testing were sent to the Radioear factory and a hearing aid was assembled using the same components as the patient had heard best with. Radioear went to extreme lengths to assure reproducibility of parts. The Radioear Company designed and manufactured much of its own production machinery in the 1930s, including an artificial ear, sound treated test enclosure, transmitters, earphones and "electro-mechanical amplifier units" (Myers, 1938).

Radioear placed over 60 Selex-A-Phones on consignment with its dealers, but when the industry switched to vacuum tube amplification (discussed below) toward the end of the decade, all were recalled in 1939 and destroyed (Berger, 1975). Sam Lybarger, engineer and later President at Radioear, wrestled with the problem of fitting over the years. The Radioear Selex-A-Phone was his invention; he received a patent for it in 1938 (Lybarger, 1938). With the advent of vacuum tube technology, Radioear abandoned the idea of made-to-order aids based on MHA findings. It was during this time that Lybarger introduced his insightful half-gain fitting rule on which many subsequent prescription formulas were patterned (Lybarger, 1944a, 1944b, 1957). He later provided Radioear dealers with the *Audiogram Analyzer*, a family of audiogram templates for each Radioear model based on his one-half-gain fitting rule, with recommended

Figure 6. Introduced in 1935, the *Selex-A-Phone* by Radioear was the first successful MHA, and was immediately copied by other companies.

Note. It facilitated fitting by the substitution method and, after the testing, the results were sent to Radioear, who built a hearing aid using components that were (theoretically) identical to those used in the MHA. The illustration clearly shows the optional earmolds, receivers, transmitters (microphones), and amplification settings that were available. An advertisement of the day promised “built-to-order” hearing aids as determined on the *Selex-A-Phone* MHA.

instrument selection and settings for audiograms that fell within a given template range (see Figure 7).

Parenthetically, Lybarger’s various contributions over the years materially changed the hearing aid industry; for example, he invented both the first wearable hearing aid telephone

coil in 1946 (Berger, 1984, p. 103; Lybarger, 1950; Lybarger & Lybarger, 2000) and the first reliable magnetic microphone (“His Hobby,” 1949; Lybarger, 1947, 1951, 1988). Versions of his bone conduction vibrator, patented in 1941, are still in use today for audiometric testing some 70 years later (Lybarger, 1941). He published comprehensive benchmark measurements on the effect of earmolds on the amplified signal (Lybarger, 1967, 1977, 1980, 1985), but one of his greatest accomplishments was his strong and respected leadership during the development (1960s–1980s) of today’s technical standards for the measurement of hearing aids, a not insubstantial achievement given the unruly and highly competitive nature of the industry. The interested reader will find further information related to stages in the development of hearing aid standards in Lybarger (1961, 1966), Lybarger & Olsen (1983), and Lybarger, Preves, & Olsen (1999).

About the time Radioear introduced the *Selex-A-Phone*, competitors entered the market with MHAs of their own also based on the substitution fitting method. It is unclear how closely they followed Radioear’s exacting attention to detail in providing one-to-one correspondence between the fitted hearing aid components and those used in the MHA. Acousticon brought out its version in 1936, the *Aurogaze*. The *Audioscope* from Sonotone appeared shortly thereafter, and claimed, depending on the source, either 288 (Hayden, 1938b) or 1,500 (Russell, 2012) different combinations of performance (see Figure 1). These MHAs also enjoyed but a brief life as they were intended to be used only with carbon-type hearing aids. The wearable vacuum tube hearing aids that were emerging in the late 1930s promised hearing aids with better fidelity, more gain, and improved frequency-gain response alternatives.

Vacuum Tube (Electronic) Amplification

Although vacuum tubes, glass enclosed devices that control current flow and amplification, had been around since the early 1900s, the large size of the early tubes required placing devices on tables or in cabinets (see Figure 8). The first hearing aid developed by Radioear in 1924 used a five-vacuum tube amplifier using radio parts built into a desk (“His Hobby,” 1949). Eventually, in the late 1930s and early 1940s vacuum tubes became markedly smaller and could be used in wearable hearing aids. As with carbon hearing aids, these body-worn hearing aids had cords connecting the various components together: the amplifier, an external receiver, sometimes an external microphone, and a separate dual-battery pack (Skafte, 1990). For the interested reader, a more detailed explanation of both carbon era and vacuum tube amplification may be found in Berger, 1984 (see Figure 9).

Because of World War II, hearing aid and MHA development stagnated during the first half of the 1940s for many companies were partially engaged in manufacturing products for the military. Sonotone, as an example, manufactured radio headsets and on the way developed a series of small magnetic

AUDIOGRAM TYPE	OPERATING GAIN FOR SPEECH-DB	INSTRUMENT SETTING						HAIC	
		Bat.	Gain Screw	#1 LF Screw	#2 LF Screw	Filter	Curve	Gain	Outp.
M	10	S76	OUT	IN	OUT	P-2951-B	I	29	120
	20	S76	OUT	IN	OUT	P-2951-A	H	33	124
	30	675	IN	IN	OUT	P-2951-A	H	37	122
	40	S76	IN	IN	OUT	P-2951-A	H	43	124
	50	S76	IN	IN	OUT	None	E	46	127
	60	S76	IN	OUT	IN	None	D	50	127
Fa	10	675	OUT	IN	OUT	P-2951-B	I	23	118
	20	S76	OUT	IN	OUT	P-2951-B	I	29	120
	30	675	IN	IN	OUT	P-2951-A	H	37	122
	40	S76	IN	IN	OUT	P-2951-A	H	43	124
	50	S76	IN	IN	OUT	None	E	46	127
	60	For Fa type audiograms with nearly normal low-frequency levels, open canal amplification (CROS) is generally preferred to above adjustments.							
R	10	675	OUT	IN	IN	P-2951-B	C	32	118
	20	S76	OUT	IN	IN	P-2951-B	C	38	120
	30	675	IN	IN	IN	P-2951-A	B	46	122
	40	S76	IN	IN	IN	P-2951-A	B	52	124
T	10	675	OUT	OUT	IN	P-2951-B	G	27	118
	20	S76	OUT	OUT	IN	P-2951-B	G	33	120
	30	675	IN	OUT	IN	P-2951-A	F	41	122
	40	675	IN	OUT	IN	None	D	44	125
	50	S76	IN	OUT	IN	None	D	50	127
P	10	675	OUT	IN	IN	P-2951-B	C	32	118
	20	S76	OUT	IN	IN	P-2951-B	C	38	120
	30	675	IN	IN	IN	P-2951-B	C	42	118
	40	S76	IN	IN	IN	P-2951-B	C	48	120

Figure 7. An example of the Radioear Auditory Analyzer that was furnished with each new hearing aid model.

Note. The fitting suggestions were based on the Lybarger half-gain rule, with modifications. This chart appeared in the 1970s in support of an eyeglass instrument, and included instructions for fitting open canal amplification using a CROS type arrangement.

receivers that were eventually adapted to body hearing aids (Pearson, Mundel, Carlisle, Knowert, & Zaret, 1946).

Toward the end of World War II, a revolutionary one-piece vacuum tube body aid, the *Monopac*, was introduced by Beltone. The microphone, amplifier, and the batteries were enclosed within the instrument's case, and all cords were eliminated except the one connected to the receiver (Lybarger, 1988; Watson & Tolan, 1949). A few years later, Beltone provided their dealers with the *Selectometer*, the first and most successful of the vacuum tube-based MHAs. It had provision for 144 different fitting combinations mainly involving receiver (and some microphone) interchanges (Berger, 1975; Seibel, 1949b; see Figure 10). In 1948, a company called Universal Hearing Institute manufactured an

MHA that included a vacuum tube body aid that left the factory only partially assembled. The front cover of the hearing aid was left off and the final configuration of the aid was accomplished by exchanging tubes and trying various receivers contained in the MHA until a satisfactory fitting was reached (Berger, 1984; Seibel, 1949a; Skaft, 1990). Other examples of MHAs used in fitting vacuum tube body aids included the Telex *Telexometer*, the Aladdin-Goldentone *Tone Tester*, the Microtone *Portable Hearing Clinic*, the Unex *Evaluator*, and the Gem *Auralgraph*; all involved fitting by component substitution (Berger, 1975; Seibel, 1949a).

As a point of interest, Carhart (1946a), in describing the program for selecting instruments used in military rehabilitation hospitals during World War II, included as part of the

Figure 8. The first vacuum tube hearing aid manufactured by Radioear in 1924.

Note. It used five vacuum tubes and incorporated the radio amplification technology of the times. A receiver was substituted for the radio's loudspeaker. The Sonotone, Acousticon, Western Electric, and Radioear companies dominated the marketplace from the 1920s to the late 1930s.

procedure the exchanging and combining of receivers, microphones, and batteries. MHAs were not mentioned, possibly because the method compared aids from different manufacturers, and each MHA was only useful with one specific brand.

The Transistor Revolution

When the industry turned to transistorized hearing instruments around 1952, the MHAs supporting component substitution were no longer useful, for by the end of 1953, vacuum tube hearing aids had all but vanished (Kent State, 2012). Also disappearing were attempts by manufacturers to provide a hearing aid with components fairly identical to those used in the MHA, a premise of the MHAs based on fitting by substitution; that is, until some 30 years later, when technological advances made it possible to resurrect the idea of one-to-one correspondence between the components in the MHA and those of the fitted hearing aid (described in later sections).

When transistor technology took over, the manufacturers were faced with a gigantic task. Product lines grew exponentially, providing a wider variety of models, frequency-gain choices, and other performance characteristics, and the

Figure 9. Two examples of vacuum tube hearing aids of the early 1940s.

Note. Two batteries were needed to provide power. The microphone was contained within the hearing aid case and the batteries worn elsewhere on the body. The lower photo with back cover removed shows the vacuum tube amplifier; note the size of the crystal microphone.

industry shifted toward ear-level instruments. The traditional method of fitting based on the physical substitution of components was useful only when fitting body aids, which were diminishing in number. Manufacturers once again reengineered the MHA, developing a number of new transistor-based MHAs that were similar in design to a speech audiometer. These MHAs provided capability for switching through a restricted assortment of amplified response shapes. The dealer sought the best fit as speech stimuli were presented at various intensity levels, response configurations, gain and output settings. The patient, listening through earphones, made decisions about quality, most comfortable and uncomfortable loudness levels, and clarity. The underlying intention was to deliver a listening experience through earphones that would be duplicated in the final fitted hearing aid(s) though this could not be accomplished for reasons discussed below.

After the evaluation was completed, it was customarily, but not always, left to the judgment of the dispenser to decide

Figure 10. A 1949 advertisement comparing the Beltone *Monopac* hearing aid that enclosed the two batteries within the case to an older model that required two external batteries. Note. The *Selectometer* MHA is pictured, with the *Monopac* hearing aid mounted in the MHA along with several optional receivers.

which particular aid(s) matched the MHA measurements. Some manufacturers provided dealers with substantial guidance, a master chart or a directory of frequency-gain curves by which the aid(s) that approximated MHA findings could be determined. Others provided very little information. The actual hearing aid that was eventually fitted was typically taken directly from the dealer's office inventory, as it was customary practice for dealers to keep on hand a representative assortment of a company's BTE, eyeglass, and body models. If not in the office inventory, the desired aid could be ordered from the manufacturer after the evaluation.

Thoughtful observers have noted the deficiencies in the use and design of the transistorized MHAs of the 1960s to 1980s. All of the factors either alone or in combination provided an amplified signal to the patient during MHA testing that was different in degree, in quality, and in equivalency to the performance of the eventually fitted aid(s). Chief among them included (a) the differences in performance at the eardrum using circumaural earphones or body-type receivers with stock earmolds, as opposed to the receiver and custom coupling of the actual hearing aid(s), (b) concerns about the type and the positioning of the microphone(s) used; some MHAs used broadcast types attached to the test console, or in

the case of a microphones placed at ear level, these were not the actual microphones used in the fitted hearing aid(s), (c) the lack of correspondence between the robust MHA circuitry and the more limited circuitry of the hearing aids that were fitted; and (d) diotic presentation of stimuli during the evaluation which differs significantly from the dichotic condition when bilateral hearing aids are fitted. Furthermore, the lack of standardization of frequency-gain response descriptions/labeling prevented the transfer of test findings between brands (Franks, 1978). For the interested reader, Bergman (1959), Nunley (1972), Resnick (1978), Voroba and Wilkinson (1988a), and Zelnick (1987) provide commentary on this subject.

Greenbaum (1968) listed the practical and cost issues faced by the hearing aid engineer in designing and manufacturing transistor era MHAs, primarily the inability to provide the many transducers, amplifier types, limiting methods, volume control tapers, and earmold attachments found in the different body, eyeglass, and behind-the-ear models that each company manufactured. And, with a few exceptions, the MHA from one company could not be used to select hearing aids from another.

A recounting of the more well-known transistor-based MHAs from the late 1950s through the 1980s would include Audiotone's *Auricon*; Beltone's *Binaural Audio-Selectometer*; Dahlberg's *Consultant*; Electone's *Electometer*; Goldentone's *M100*; Maico's *Precision-Ear*; Otari's *Auditory Analyzer*; Qualitone's *Acoustic Appraiser*; Telex's *Mark III Hearing Aid Simulator*; Vicon's *Metri-con*, and Zenith's *Auralyzer*. Some were more elaborate than others; many had two channels, masking, compression circuitry, and eventually, ear-level transducers, most provided some form of speech testing capability and many included an air and bone conduction audiometer (see Figure 11). Notably, a few companies developed MHAs that involved unique proprietary approaches to fitting, discussed in a later section.

The ASHA, HAIC, and the MHA

In the mid-1940s, audiology, as a newly constituted area of study, was in the process of applying for entrance to university graduate programs. At the time, it was not typical for audiologists to dispense hearing aids and a university curriculum that included the dispensing of hearing aids would have been viewed unfavorably. The audiologist would administer tests of speech intelligibility in a sound field, allowing the patient to listen through several different hearing aids. A preferred hearing aid would be determined and the patient would be referred to a hearing aid dealer to purchase the device, a process referred to as the comparative hearing aid evaluation procedure (ASHA, 1967, pp. 14-15; Carhart, 1946a, 1946b, 1946c, 1950, 1959). As audiology clinics proliferated, the *comparative* procedure placed a tremendous burden on manufacturers (and/or dealers), who bore the expense of placing aids in the facilities. The

Figure 11. Two examples of 1970s transistorized MHAs with advanced features, including pure tone air and bone conduction testing, narrow band masking, MPO controls, optional earphones and binaural live and taped speech testing.
 Note. Above, Telex Mark III Hearing Aid Simulator; below, the Qualitone Acoustic Appraiser.

American Speech and Hearing Association (ASHA) reported that some clinics had as many as 40 aids of various makes and models in inventory and the Hearing Aid Industry Conference (HAIC) estimated the inventory in clinics amounted to approximately US\$1,000,000 (in 1959 dollars), plus US\$250,000 lost annually as discontinued hearing aids were replaced with new (ASHA, 1967; Bergman, 1959; Stutz, 1968). In 1978, Franks calculated that at some point in the years ahead it would cost the industry upward of US\$7,000,000, as the number of audiologists, companies, and dispensers was continually expanding (Franks, 1978).

In an attempt to alleviate this costly arrangement, representatives of the ASHA and HAIC held joint discussions exploring the possible use of MHAs in clinics rather than live aids (Bergman, 1959). Before agreeing to their suitability for clinical use, the ASHA submitted a number of issues they felt should be addressed in addition to the inadequacies

noted above. They indicated that distortion levels in hearing aids were an important factor, as were the characteristics of the various compression circuits, and both should be somehow accounted for in using the MHA. They also requested that dealers should loan the recommended hearing aid to the patient for follow-up testing at the clinic to confirm the prescribed fitting. Future joint discussions were suggested, but industry went ahead on its own, investing in 15 prototypes, designed and manufactured by Knowles Electronics, an industry supplier (Berger, 1975). Six were eventually placed in clinics and, to no surprise, all were determined to be of little use (ASHA, 1967, p. 17; Berger, 1975). The initiative died a quiet death as the companies totted up the initial expense and the resources it would take to keep the MHAs up-to-date with new product introductions (Stutz, 1968). Furthermore, the industry realized it could not provide a design that would be truly universal; that is, accurately simulate the performance of all products from all the manufacturers (Berger, 1975; Greenbaum, 1968; Stutz, 1968).

Early Audiology-Industry Relationships

During the 1950s and 1960s, there was an undeniable atmosphere of antagonism between audiology and the hearing aid industry (Fogel, 1965; Millin, 1984). At that time, audiologists believed that the profession had eliminated the possibility of conflict of interest by choosing not to dispense hearing aids. Comparing their daily practice to that of the hearing aid dealer, audiologists determined that the practice of dispensing hearing aids was monetarily driven. Under the care of a nondispensing audiologist, patients were assured of protection from high-pressure salesmanship as the audiologist would make a recommendation based on objective observations made during the comparative fitting process. Dealers were understandably chagrined, for they felt audiologists were competing unfairly for clients from under the protective umbrella of institutions. In the words of Kenneth Johnson, then Executive Secretary of the ASHA, dealers viewed the "addition [of audiologists to the rehabilitation team as] . . . an unwarranted intrusion" (Fogel, 1965, p. 10). Furthermore, dealers were certain, based on their experience, that the comparative method was not an unbiased procedure (Millin, 1984; Skafte, 1990, p. 11).

Eventually, research showed that the comparative evaluation method indeed was not valid. (Carhart, 1975; Chial & Hayes, 1974; McConnell et al., 1960; Schwartz, 1982; Shore, Bilger, & Hirsh, 1960; Walden, Schwartz, Williams, Holum-Hardeggen, & Crowley, 1983). In 1980, Studebaker and Hochberg observed,

Thirty years of extensive research have failed to demonstrate that hearing aids can be chosen reliably or validly by [the comparative] method in a reasonable period of time. The field of audiology has paid dearly for failing to recognize and heed the implications of published research concerning this method's weakness. (p. xiii)

Despite an awareness of the lack of clinical validity, recommendations using the comparative evaluation procedure endured in clinics well into the 1980s. As a result, some audiologists accustomed to the reliability and relative precision of diagnostic measurement were polarized by the negative experience of comparative fitting and avoided involvement in hearing aid matters. (Elpern, 1973).

MHAs in the Audiology Clinic

Given their unfavorable attitude toward the hearing aid industry, it is not surprising early audiologists routinely disparaged MHAs (ASHA, 1967; Bergman, 1959). The conventional wisdom was that MHAs were used to convince patients to purchase bilateral hearing aids when they were not indicated. Audiologists believed this recommendation was not supported by research studies available at the time. These studies showed little or no benefit from binaural compared to monaural amplification and, therefore, bilateral recommendations were usually avoided (Carhart, 1975; Craine, 1988; Pollock, 1975). Obviously there was truth on both sides of the question, but the tenor of the times and the lack of credible evidence precluded discussion. In point of fact, companies routinely encouraged their dealers to use the MHAs to demonstrate the superiority of binaural hearing as opposed to monaural.

Audiologists also held that the quality of amplification afforded by the MHA was superior to the degraded signals provided by hearing aids (ASHA, 1967, p. 17; Bergman, 1959; Craine, 1988; "Final Report," 1978; Franks, 1978; Resnick, 1978). In most instances, the audiology community was correct, for MHAs were usually constructed with electronics and transducers that were superior to or different from the aids that were fitted.

The hearing aid industry came under scrutiny in public hearings by both the Food and Drug Administration (FDA) and the Federal Trade Commission (FTC) in 1976-1978. The FTC submitted regulations for comment that industry considered punitive and restrictive. One not well-known provision in the proposed regulations concerned MHAs; the FTC intended to essentially eliminate their use. In the Proposed Trade Regulation Rules, Section 440.7, *Selling Techniques*, it was stated that

No seller shall utilize any device to demonstrate the performance which a consumer can expect from a hearing aid, when the performance of such a device differs in any material respect from that of said hearing aid. (Federal Register, 1975, p. 26648)

Testimony was submitted by industry representatives to show that this was a distorted representation of the MHA's fundamental purpose, which was, in essence, an aid for evaluating a patient's candidacy for amplification and for providing fitting information. In the end, the proposed regulations were never enacted. The regulatory proposals of both government agencies were strongly influenced and encouraged

by the audiology profession's leadership, whose goal was to establish audiology through legislative initiatives as the primary gatekeeper for the delivery of hearing care in the United States ("Final Report," 1978, pp. D-72, 73, 75, 76; Fogel, 1974; Johnson, 1976; Viewpoint, 1976).

Despite dissatisfaction with the comparative evaluation method, the use of an MHA was not ordinarily considered as an alternative in the clinic, for when one examined contemporary MHAs objectively, it was clear that the fitting machine routine also had shortcomings. Nevertheless, Franks reported that during the 1970s some clinics did use commercial MHAs to arrive at a "generic form of amplification" (Franks, 1978, p. 111). Here the audiologist, instead of conducting a full-blown comparative evaluation, recommended hearing aids based on the findings of the MHA, without specifying brand or model, or alternatively, recommended hearing aids provided by the manufacturer of the MHA. The dealer fitted the aid that was selected according to the MHA specifications, and the patient was followed up in the clinic by an audiologist (Craine, 1988). Gillespie, Gillespie, & Creston (1965) compared the traditional method of hearing aid evaluation to results obtained on an MHA and concluded both evaluation methods gave equivalent results and both were comparable in time required and reliability. In a 1978 study, Viehweg reported that more than 90% of the patients who were evaluated in their clinic with an MHA and who subsequently purchased aids based on the MHA findings were satisfactorily fitted. Welch (1988) described a special type of MHA that used discrete signals across frequency as stimuli instead of speech to prescribe amplification, and provided case studies of successful fittings. Similarly, Crouch & Pendry (1972a, 1972b) applied for and received approval from the Florida Department of Health and Rehabilitative Services to use this system, known as *otometry* (discussed below), as an alternative method of fitting hearing aids in a children's hospital.

Many audiologists felt that by not dispensing, the hearing aid world was passing them by (ASHA, 1967, pp. 57-66; Curran, 1976; Cutler, 1975; Elpern, 1973; Millin, 1984). It was obvious that hearing aid technology was improving rapidly and that amplification was the most crucial part of the rehabilitation process, but audiologists were handcuffed in their desire to participate in a more constructive manner (ASHA, 1967, pp. 60, 65; Cutler, 1975). This state of affairs lasted until the ASHA lifted the prohibition against audiologic dispensing of hearing aids in 1978.

Research Using MHAs

Despite their limitations, MHAs have been used to conduct hearing aid research. In 1947, in two independent studies, investigators at Harvard (Davis et al., 1947; [usually referred to as the Harvard Report]) in the United States and in England (Medical Research Council of Great Britain, 1947; [usually referred to as the Medresco Report]) assembled

instrumentation using the high fidelity (vacuum tube) audio components of the time. These specially constructed MHAs were essentially prototype speech audiometers incorporating a limited set of frequency-gain characteristics with which to measure word intelligibility. The intention of both research groups was to discover the frequency-gain response(s) that would be most useful for the majority of patients with different hearing losses. It was not an uncommonly held opinion that the response curves of the relatively crude hearing aids of the day could not possibly “. . . compensate for the sharp variations in individual hearing defects” (Watson & Tolan, 1949, p. 368; also see Davis & Silverman, p. 325). These early landmark studies made a large impact but had the unfortunate effect of slowing progress, for both suggested that hearing aids having a “uniform,” flat, or a slightly rising response, were sufficient for most losses. This recommendation was echoed by other influential investigators, including Duggan (1949), Pothoven (1948), Radley (1950), and Sheets & Hedgecock (1949). In the United States, the Harvard Report authors (Davis et al., 1946) were openly critical of spending any time on a comparative hearing aid evaluation, a conclusion that sharply disagreed with the traditional comparative procedure described by Carhart (1946a, 1946b, 1946c). They asserted the procedure that had been developed in military hospitals to select aids were inconclusive and led to a “false idea of precision” (Davis et al., 1946).

The merits of “selective amplification,” defined for our purposes as tailoring and adjusting the frequency-gain response to the general shape of the patient’s thresholds, as opposed to fitting an instrument with a uniform response irrespective of threshold configuration, was an issue that dogged hearing aid fitting for some years (Carhart, 1975; Jerger, 1999; Pascoe, 1978). Early commentators (Brady et al., 1938; Carhart, 1946a; Hayden, 1938b; Jones & Knudsen, 1938; Myklebust, 1943), and even the authors of the Harvard Report prior to their experiments (Davis et al., 1946), thought frequency-gain manipulation obvious; it seems clear today that response modification is essential and that one or two response shapes are insufficient. But the authors of the Harvard Report were the leading otologists, researchers, and acoustic scientists of the day, and immensely influential. The report strongly influenced many in a profession that was in its infancy with few authority figures of its own. Carhart, ever the scholar, accepted the results of the Harvard Report, and incorporated its suggestions into his lectures in the classroom even though they seemed to contradict the comparative protocol he helped develop in military hospitals (Carhart, 1946b, Carhart, 1950; E. R. Harford, personal communication, 2012). At the same time, however, the audiologists who were doing comparative hearing aid evaluations in the clinic continued to use some form of selective amplification, for they found patients did better with different receivers and settings (E. R. Harford, personal communication, 2012; Lybarger, 1978).

The Harvard Report also influenced some manufacturers who began to provide only uniform, restricted response hearing instruments, a much less expensive manufacturing proposition (Watson & Tolan, 1949, p. 372), and a practice that depreciated the utility of the MHA. In time, it became clear there were many deficiencies in the Harvard Report related to the equipment and procedures used. These included the absence of the body baffle effect during testing (Watson & Tolan, 1949, p. 380) and low frequency leakage from under the patient’s circumaural earphones (Cox & Studebaker, 1977), both of which meant that the subjects were listening to speech signals having greater emphasis in the high frequencies, and as well, patient selection issues, for a goodly number had conductive impairments (Lybarger, 1978; Resnick, 1978).

In later years, using digital MHAs of advanced design, investigators at the Central Institute for the Deaf reported, among other findings, that contrary to the Harvard Report, an individualized frequency-gain response curve based on a patient’s suprathreshold findings provided superior speech recognition (Engbretson & Miller, 1982; Miller et al., 1980; Pascoe, 1975, 1978; Skinner, Karstaedt, & Miller, 1982). Pascoe (1975) stated flatly that “the results . . . strongly support the hypothesis of selective amplification.”

In the 1980s, an extensive series of investigations was conducted at the City University of New York (Levitt & Collins, 1980; Levitt, Neuman, Mills, & Schwander, 1986; Levitt, Sullivan, Neuman, & Rubin-Spitz, 1987; Levitt, White, & Resnick, 1976) in which versions of a specially designed digital wearable MHA were developed to evaluate three different adaptive paired-comparison procedures for prescribing frequency-gain curves. In discussing the clinical usefulness of adaptive protocols, the authors pointed out that for a given patient, the frequency-gain curve selected when using an adaptive procedure would change if different test materials, competition, or talkers were used. They found the most efficient of the procedures (Simplex) took, at minimum, 10 min to accomplish. However, their results also confirmed “the importance of individualized prescriptive fitting of hearing aids” (Levitt et al., 1987, p. 51).

The studies above are notable not only for the results they produced but also to point out that at least in some laboratory settings the MHA was considered to be a most useful and economical way to further study objectives.

The Hearing Aid Dealer and MHAs

It is worth repeating that for the 50 years previous to audiology’s beginning in the late 1940s, and throughout the years that followed up until the 1980s, nearly all hearing aids were fitted, sold, and delivered by the hearing aid dealer. Clinical referrals of instruments began to grow but the aids that were referred were sold by dealers. Despite being deprecated by audiologists, for many hearing aid dealers the transistor-based MHA was their most used fitting tool (Arnold, 1978;

Figure 12. The Zenith *Auralyzer*, a late 1970-1980s MHA that provided comprehensive data relating the MHAs findings to specific Zenith hearing aids.

Note. Despite detailed guidelines, the *Auralyzer* implied more fitting precision than could be delivered for, as with nearly all MHAs, the acoustic signal of the fitted hearing aid(s) did not match that of the MHA.

Briskey, 1988; Curran, 1972; Greenbaum, 1968; Nunley, 1972; Stutz, 1968). The results could provide a gross but useful approximation of the individual's UCL, MCL, or peak gain requirements, an estimate of word recognition ability, and an indication of the required slope below 2000 Hz (Craine, 1988; Franks, 1978). Ideally, using these results, the dealer was able to make useful fitting decisions. However, some companies provided more helpful information about instrument selection than others.

The Zenith *Auralyzer* was a representative example of an MHA that provided dealers with fairly extensive guidance (see Figure 12). Zenith analyzed the performance of all their aids at all settings and printed out 2cm³ frequency-gain curves of those aids that most closely matched a given response configuration on the *Auralyzer*, in descending order. The dealer was provided with a booklet containing this data, which showed the aid's performance and included the effect of the earmold type used on the frequency-gain curve. Obviously a great deal of time and effort went into Zenith's attempt to make life easier for dealers, but shortcomings in the *Auralyzer's* design precluded fitting accuracy. One obvious flaw was that the *Auralyzer* had microphones embedded on the console surface although the MHA did have ear-level BTE receivers (Berger, 1975; Franks, 1978).

One manufacturer, Otariion, featured plug-in transducers that could be mounted on a universal adjustable eyeglass frame (see Figure 13). It was claimed by using Otariion's *Auditory Analyzer* the dealer could "test and prescription fit at ear level," and duplicate "the exact response of each and every Otariion aid with which you work . . . spectacle, behind the ear, pocket and bone" (Otariion, 1962, p. 6). Clearly, the outcomes they promised were neither possible nor likely because of the necessary compromises inherent in the design of transistor-based MHAs (Greenbaum, 1968).

Figure 13. An advertisement for the transistor-based Otariion *Auditory Analyzer* from the early 1960s.

Note. As usual, the ad copy exceeded the probability that the MHA could actually deliver what was promised. The unit's clever design, however, recalls to mind the carbon era and vacuum tube MHAs that supported the substitution fitting methodology.

Figure 14. Illustration shows a hearing aid dealer using an early version of the Audiotone *Auricon*, which could be obtained with or without capabilities for audiometric testing.

Note. Here the pure tone and speech audiometer (left) is separate from the MHA on the right.

On the opposite end of the spectrum was Qualitone, who provided no reference guide whatsoever about which of their aids matched the readings obtained on their *Acoustic Appraiser* (Figure 11) nor did Dahlberg's *Consultant* include that information. Most manufacturers in the 1970s, because industry marketing and sales programs were under increasing scrutiny by the FDA and FTC and as more rigorous state licensing laws were emerging, focused on encouraging dealers to use the audiometer section of the MHAs to learn and use pure tone and speech testing properly (see Figure 14).

Good, Better, Best, Best of all

Amplification technology and component miniaturization advanced rapidly as each decade passed, providing along the way greater opportunities to develop more sophisticated and beneficial MHAs. Over the years a continuing, pervasive, underlying goal was to design and manufacture MHAs that provided one-to-one correspondence with the fitted hearing aid. Below are examples of thoughtful attempts to do so by four manufacturers, Audiotone, Vicon, Shalako, and Bausch and Lomb, each of whom achieved differing levels of realism. Audiotone capitalized on the high frequency response configurations that manufacturers were increasingly able to provide, Vicon introduced a fitting method using nonspeech stimuli rather than speech signals, and both Shalako and Bausch and Lomb incorporated forced-choice adaptive selection procedures in their fitting software.

Audiotone: Good

In the 1960s Audiotone introduced a widely used, very popular MHA called the *Auricon* (see Figure 15). Early ads advertised “Factory Certified Custom Fitting . . . instrument[s] engineered specifically [to your customer’s] hearing impairment” (Audiotone, 1962; “Selection Instrumentation/Master Hearing Aids,” 1988). The components used within the *Auricon* were represented to be equivalent to those installed in the aids (Langford, 1977). The *Auricon* was designed to measure most comfortable level (MPO) and intelligibility as the tester varied speech presentation across a family of five (later six) response configurations, varying from an essentially flat frequency response to an approximately 35 dB/octave rise between 500 and 4000 Hz. After testing, an aid ordered in the desired style containing the “prescribed” performance was returned (Craine, 1988; Franks, 1978; Langford, 1977). The aid’s performance data were obtained on a 2cm³ coupler at the factory, but despite having similar electronics and a frequency-gain curve theoretically similar to that provided by the MHA, the performance on the patient, of course, was not equivalent (Nunley, 1972; Shaw, 1974).

Much of the *Auricon*’s popularity and effectiveness could be traced to Audiotone’s market-savvy incorporation of high frequency emphasis response shapes both in the *Auricon* and in their hearing aids (Figure 16) at a time when interest in the influence of higher frequencies on improving intelligibility was being rediscovered (Dodds & Harford, 1968; Hodgson & Murdock, 1970; Hudgins et al., 1947; Sung, Sung, & Angellelli, 1971; Thomas & Pfannbecker, 1974). Until the late 1960s, unaided word recognition scores obtained with the flat response audiometric earphones were considered to be the gold standard for, by comparison, the distortion and other deficiencies in the early hearing aids might be expected to (and often did) result in degraded speech scores (Carhart, 1970; Craine, 1988; Dillon, Byrne, & Upfold, 1982; Hirsh, 1952, p. 299). As ear-level instruments improved and open canal fittings increased, this proposition was eventually

Figure 15. Top: A very early model of the *Auricon*. Note the use of body receivers with stock molds; microphones were mounted on the faceplate. Bottom: A much later iteration of the *Auricon* featuring true binaural amplification, and if needed, masking noise when testing one ear only. This model utilized microphones and receivers mounted in BTE cases.

discarded as it became clear that word recognition scores depended on the conditions of the test (Christensen, Lee, & Humes, 1994; Dodds & Harford, 1968; Frank & Karlovich, 1976; Hodgson & Murdock, 1970; Jetty & Rintelman, 1970). Audiotone eventually moved somewhat away from their custom fitting program but was among the first U.S. manufacturers to introduce a commercially available programmable digital hearing aid, the Audiotone 2000 (Craine, 1988; Nunley, Staab, Steadman, Wechsler, & Spencer, 1983).

Vicon: Better

In the 1960s, Vicon Hearing Instruments introduced a unique type of MHA, the *Meticon*, available in several versions over the years (Nunley, 1972; “Sound Pressure Instruments,” 1977; Vicon, 1962; see Figure 17). It facilitated a fitting system that was essentially an elaboration of frequency-gain

Figure 16. A family of response curves obtained on a special Audiotone hearing aid.

Note. The responses progress from R1 (flat) through R6 (approximately 35 dB gain between 500 and 4000 Hz) and are intended to represent the six responses available on the *Auricon*.

selection based on most comfortable loudness levels first described by Watson and Knudsen (1940). Loudness levels were measured using damped wave trains (DWT), repetitions of periodic tone pulses that decayed at a rate of 10% per cycle, presented at discrete frequencies from .5 to 6k Hz (Victoreen, 1968). Research by John Victoreen, who founded Vicon, suggested the normal ear perceived loudness levels of DWTs to be most comfortable at approximately 72 dB SPL across frequency (Victoreen, 1973, 1974). Patients adjusted a “laboratory test aid” to where a 72 dB DWT signal at 1000 Hz sounded most comfortable. Without changing the VC setting, the increase in DWT intensity that it took to achieve MCL at each frequency became the amount of 2cm³ coupler gain prescribed to correct the hearing loss (Welch, 1988). The data were sent to Vicon who returned a “prescription hearing instrument” having the “correct” frequency-gain response (Victoreen, 1973; Welch, 1988). The Vicon Company and its *otometric* fitting method had a small but loyal group of followers over the years, but the difficulty of manufacturing prescription aids economically and the advent of custom ITEs led to several changes in ownership and final bankruptcy in 1981.

Shalako: Best

Another manufacturer, Hearing Health Group (known also as Shalako), introduced an MHA and fitting procedure, “selective spectrum amplification,” described in a series of patents granted in the 1970s (Stearns, Blackledge, & Rohrer, 1974; Stearns & Elpern, 1974; Stearns & Lauchner, 1974). The Shalako instrumentation, which was developed with the assistance of Barry Elpern, PhD, one of the earliest dispensing audiologists (Jerger, 1999), held considerable interest for audiologists who were contemplating dispensing. It provided a fitted hearing aid(s) that contained components nearly identical to those with which the patient was tested,

resurrecting the original idea of one-to-one correspondence introduced by Radioear in the 1930s (Holmes, 1976; Lawrence, Halladay, & Blackledge, 1977a, 1977b; Stearns, Lawrence, & Rohrer, 1979).

A universal “test hearing aid” containing ear-level transducers and a set of filters (band-pass, low pass, and high pass) was connected to the MHA (called the *Prescriptor*; see Figure 18), which was manipulated by the examiner. Using a forced-choice protocol described in the patents, the MHA exposed the listener, through the test hearing aid, to a limited variety of amplified response choices. On completion, the reciprocal of the selected frequency-gain response was immediately transferred electrically to a wearable ear-level instrument that had the same amplifier, filters, and transducers as the test aid.

This was a daring concept for the time, but the Shalako methodology pushed against the limits of what was achievable given the technology available. Digital amplification and transducer technology were undergoing rapid change requiring substantial ongoing resources to stay current. The company lingered into the early 1980s, eventually falling victim to competitive forces and the popularity of custom aids.

Bausch and Lomb: Best of All

In the late 1980s, another company took the bold step of manufacturing made-to-order aids having one-to-one correspondence with the components used in the MHA (“Selection Instrumentation/Master Hearing Aids,” 1988; Voroba, 1984). The *Programmable Auditory Comparator (PAC)*, designed and patented by Barry Voroba, PhD, an audiologist at Starkey Labs, incorporated the same micro-circuitry and transducers in the hearing aids as were in the MHA. Brought to market by Bausch and Lomb, the device consisted of a microprocessor-based patient-operated console and a separate operator’s console (Voroba & Wilkinson, 1988a, 1988b, 1988c; see Figure 19). The patient was fitted with one of five available premanufactured ITE ear shells complete with vent type/size based on audiometric findings into which a “hearing aid test module” was inserted (Voroba & Oberlander, 1989). The hearing aid test module could be manipulated by the patient to provide alternative performance settings. The patient listened to prerecorded word lists delivered in a calibrated multispeaker sound field, using a preprogrammed adaptive test protocol. When a preferred combination of components was chosen by the patient, an amplification module having the exact specifications, amplifier, and transducers as the test assembly was snapped into the ear shell (Voroba & Wilkinson, 1988a).

Although the eventual amplification module that was installed in the shell duplicated the components and settings of the test module, it is clear there had to be slight variations. The *PAC* saw use for a few years in selected markets, but the ascension of computer-based software fitting programs and programmable hearing aids overtook it. Furthermore, reliance on modular fittings was a drawback, for modular aids

Figure 17. Left: An advertisement of an early version of the Metricon “pressure measuring instrument,” an MHA that facilitated fitting by testing with damped wave trains (see text). Right: Shows a later configuration, with the entire MHA contained within bilateral supra-aural earphones.

Figure 18. Shows the *Prescriptor* MHA by Shalako. Note. The operator manipulated filter settings enclosed in test hearing aids as the patient listened to forced choice speech stimuli. The final setting was electrically transferred to hearing aids containing the same filters and transducers as the test instruments.

have always proven to be markedly less successful than custom-built instruments in the U.S. market.

The Emergence of Computers in Hearing Aid Fitting

The advent of threshold and supra-threshold-based prescriptive formulas that were proposed in the 1970s to 1980s led to

changes in MHA function and design. (The interested reader will find further information on the development of prescriptive formulas in Dillon, 2001; Hawkins, 1992; McCandless, 1988; Staab, 2000; Traynor, 1997; and Zelnick, 1987). All of the commercially available MHAs described in earlier sections of this article involved the patient listening to speech signals. (The Vicon MHA was the lone exception, where the patient made loudness judgments of nonspeech stimuli.) The conventional speech-based MHA became less useful when custom aids rose in popularity in the 1970s to 1980s, for selection of performance was usually decided by the manufacturer. The process of fitting changed from a reliance on evaluative speech testing to one of predicting appropriate gain-frequency configurations based on audiometric threshold data. Microprocessor and computer algorithms were developed to calculate presumptive response options, and various in-office verification procedures were used to ascertain acceptability or not of the prescription, including real ear measurements (described below), speech testing, and patient testimony.

Factory-Based Selection of Performance

As noted above, the selection of frequency-gain response configurations in custom aids was normally decided at the factory. Manufacturers developed proprietary computer-mediated software that selected the circuitry and transducers (and thus the frequency-gain response) for installation in their products. Starkey Labs, for instance, who popularized the custom aid, developed algorithms based on Lybarger's (1944a, 1944b) half-gain fitting concept modified according

Figure 19. Taken from the original patent for the *Programmable Auditory Comparator*, the drawing shows the two consoles, one for the operator, and the other for the patient.

Note. Listening through test hearing aids to forced choice stimuli in a calibrated sound field, the patient selected the best circuit/transducer combination. These choices were then installed in the final fitted hearing aids.

to style of aid, UCL measurements, and manufacturing experience. The decision by manufacturers to involve computers in the selection of custom hearing aid performance was an early expression of the proprietary computerized fitting software programs in use today.

The perceived as well as the actual advantages of custom amplification was tempered by the fact that a very large number had to be returned for frequency-gain response changes, an untidy and costly situation. That reality, and in response to the many professionals who wished to choose the frequency-gain curve themselves, led Starkey to introduce a short-lived MHA called the *CE Evaluator* (Franks, 1978; Green, Day, & Bamford, 1989; "Sound Pressure Instruments," 1977; see Figure 20). It featured ear-level microphones and

Figure 20. The *CE Evaluator* MHA by Starkey contained a wide selection of circuits, components, ear-level transducers and shell configurations for selecting performance.

Note. The results of the testing were sent to Starkey who manufactured custom instruments that approximated the findings supplied by the hearing aid professional.

receivers enclosed within ear shells of different shapes and vents. The use of hearing aid components and circuitry in the MHA allowed the tester to order an aid(s) having approximately identical characteristics. It was not widely distributed, for several interrelated strategies for fitting hearing aids were capturing interest about this time as more and more audiologists entered into dispensing.

Dedicated Probe-Microphone Measurement

Prescription formulas combined with computer-based probe-microphone instrumentation led to a fitting methodology that enabled prediction and verification of amplification in the real ear. Probe microphone assemblies had been in limited use in the United States since the early 1980s (Northern, 1992), but prefitting and verification measurements became clinically feasible when dedicated computerized real ear measurement (REM) instrumentation entered the marketplace in the late 1980s (e.g., Acoustimed HA-2000; Fonix 6500; Madsen IGO 1000; Rastronics CCI-10). These computer-mediated real ear measurement instruments afforded the practitioner the ability to order and fit custom aids having coupler gain and output specifications specifically tailored to the individual patient's needs (Mueller, 1992) and, as such, functioned as MHAs.

The original versions of the more popular prescription formulas used at that time (see Berger, Hagberg, & Rane, 1977; Byrne & Dillon, 1986; Byrne & Tonnisson, 1976; McCandless & Lyregaard, 1983; Seewald & Ross, 1988; and Seewald, Ross, & Spiro, 1985) have since been extensively reviewed and validated by research until they have become

Figure 21. Two types of Widex Quattro microprocessor-based controllers that sent wireless signals to Widex programmable hearing aids for manipulating performance.

Note. The programmers (MHAs) were loaded with an individual's thresholds and other information and, after calculating the preferred response, gain, and output options, this information was sent to the hearing aids. The emergence of programmable amplification systems led eventually to today's modern computer-mediated fitting algorithms.

the foundation of the modern algorithms provided by manufacturers in their fitting software.

The Programmable Hearing Aid and the MHA

Concurrent with the advent of REM and prescriptive formulas, advances in digital technology provided impetus for the development of programmable hearing aids (Bentler, 1991; Mueller, 1994; Staab, 1990). Programmable hearing aids were preloaded with a limited set of frequency-gain performance options and/or other amplification alternatives. Early versions involved digitally programmable analog circuitry, but eventually microprocessor miniaturization made all-digital programmable instruments possible. Host computers or programming devices (MHAs) sent controlling signals to the hearing aids either by wire (e.g., Bernaphon-Maico PHOX, 3M Memory Mate), infrared (e.g., Philips FARO, Audio Science), or radio waves (e.g., Widex QUATTRO; see Figure 21.). With some systems, the patient's pure tone thresholds (and where indicated, loudness measurements) could be loaded into the programmer and a prescription formula selected the closest frequency-gain curve in the hearing aid. The professional could rotate between frequency-gain settings as desired, constituting a welcome step-up from the need to manually manipulate adjustments with onboard trimmers (Preves, 1993). More importantly, all substantive objections to MHAs in years past were overcome, for the patient was fitted with the exact response, performance, and instrument that had been selected during the MHA evaluation (Craine, 1988).

In summary

The combined experience gained by manufacturers in the development of (a) factory-developed computer-based software for selecting custom aid circuitry and transducers, (b) the computer-based probe microphone instrumentation that facilitated real-ear fitting and verification using prescriptive formulas, and especially, (c) the devices (MHAs) that controlled programmable hearing aids, laid the groundwork for today's sophisticated computer-based fitting systems. Modern computer-mediated fitting software and advanced signal processing now allow nearly unlimited changes to the entire electroacoustic performance of the hearing aid, resulting in an essentially full realization of the MHA as first imagined. Previously, programmable aids and controllers provided only a fixed set of stored frequency-gain options and were limited by the relatively rudimentary level of digital technology and the unrefined software of the time. It could be suggested that yesterday's programmable aids compare to the early PAC-MAN or Pong arcade games of 35 years ago, whereas today's computer-based fitting systems mirror modern-day interactive gaming consoles.

The Role of the MHA After the Initial Fitting

An appropriate description of the modern fitting process recognizes two complementary actions: first, the selection of the initial fit and, second, adjustment or fine-tuning of the original fitting parameters. Most fitting procedures, dating back to the original MHAs, have been concerned with calculating or discovering the initial frequency-gain response. Less emphasis has been placed on modification or follow-up to the original prescription. Humes (1988) comments on this, saying,

... the hearing instrument selection process should be recognized for what it is—a first step in the rehabilitative process. The explosion of interest in the prescription of electroacoustic characteristics . . . has perhaps brought too much focus on this aspect of the selection and evaluation process. (p. 25)

No fitting is immediately correct in all respects; the *best fit* afforded by prescriptive algorithms is in reality a *best guess* that lacks a certain level of exactness and specificity. There are any number of well-known reasons why we cannot arrive at a greater level of precision, including issues of temporal and frequency resolution in the cochlea, disruption of loudness relationships, age, previous listening experiences, choice of prescriptive formula, and the test-retest variability of the diagnostic techniques. Consequently, the working out of after-fitting issues becomes just as important as the initial prescription in assuring satisfaction.

It is here that the usefulness and relevance of the MHA rises far above the level for which it was originally conceived;

its role in resolving postfitting issues was hardly contemplated in the past. Until the advent of modern computing technology, it was difficult to provide the level of resolution to problems that is available today. Today, each manufacturer furnishes a proprietary suite of issue-resolving programs in their fitting software. These usually include, but are not limited to, four general categories, in no particular order, (a) fine-tuning of electroacoustic performance, (b) real-ear measurements, (c) manufacturer's fitting software, and (d) data-logging information.

Fine-Tuning

We use the term *fine-tuning* to describe the actual changes made to the electroacoustic performance of the aid during and after the initial fitting. Not surprisingly, a review of early and even recent hearing aid texts and journals shows occasional sections devoted to earmold modification but, with few exceptions (notably, Dillon, 2001; Jenstad, Van Tassel, & Ewart, 2003; Kuk, 1999; Nelson, 2001; and Sabin, Harkies, Marrone, & Dhar, 2011), little systematic fine-tuning information. One reason for the paucity of information is that fine-tuning possibilities prior to computer-based software were fairly crude and restricted and, in the case of custom aids, significant response changes were only available from the manufacturer.

Modern fitting and fine-tuning software allows the professional to adjust nearly every variable necessary to resolve a fitting, including discrete gain and maximum output changes in 2 dB (or fewer) increments across frequency, changes in compression threshold and ratio, and attack and release times, adjustments for gain at different input levels, and initiation, modification, or elimination of signal processing features such as frequency lowering, noise management programs, and directional microphone sensitivity as well as independent manipulation of the foregoing characteristics within each separate program. In addition to the customary method of specifying initial performance, most manufacturers also provide programs for initial fitting and postfitting adjustments based on in situ threshold values. Furthermore, the renewed interest and technological improvements in instrumentation dedicated to tinnitus treatment also requires specialized software for fitting and for subsequently adjusting performance features.

Patient-Driven Fine-Tuning

Fine-tuning based on the patient's report or complaint, no matter how soundly executed, is an inefficient notion. The professional cannot experience the patient's hearing; instead it requires properly interpreting the patient's descriptor. One interesting solution is *Soundpoint* (Starkey Hearing Technologies), a patient-driven software feature dedicated to resolving this issue. This computer-facilitated software feature provides a real-time method for allowing patients to

fine-tune their hearing aids themselves without the need for interpretation by the professional (Valentine, Dundas, & Fitz, 2011), a method of adjustment that can, in effect, function similarly to a user-controlled MHA. Using any computer mouse or Apple's iPad, the patient can seamlessly navigate by tracing a path through a space shown on the computer screen. Embedded in this space are 64 possible offsets to the prescribed frequency-gain response and compression characteristics. As the cursor moves around the screen these changes are heard in real-time. When the patient finds a sound quality they determine to be pleasing, a tap of the screen or mouse will assign the current gains as a preferred listening setting. During this fine-tuning process, the patient has the option of listening in quiet or any sound source of his or her choosing; the software media player includes noisy environments that can be played through any computer speaker.

Adaptive Fine-Tuning

Some inexperienced users react negatively to the initial prescriptive fitting afforded by a given proprietary software program. The problem may be related to many factors but often it is a function of too much prescribed gain. Professionals can deal with this by either actively managing the fine-tuning changes that may be required, or by assuming that in time the patient will adapt to the amplified signal without the need for intervention. An alternative strategy utilizes hearing aid features that adapt the hearing aid's gain level automatically over time. An example of an adaptive change program that can be activated within the instrument's software is the self-learning volume control, where the preferred gain setting is determined based on the patient's volume control changes over time in various environments. Another solution is the *Automatic Adaptation Manager* (Unitron), an algorithm that gradually raises the level of amplification from below prescribed targets over a given period of time (Hayes, Pumford, & Cornelisse, 2012; Pumford, Hayes, & Cornelisse, 2012). In both instances, the professional has the option of selecting these management tools from the fitting software, which includes the ability to configure starting points and the level of change preferred.

Real-Ear Measurement

Prior to the availability of today's hearing aid programming software, real-ear measurement was the only method for understanding the in situ hearing aid response. With the development of programming software, an estimate of the in situ or coupler response of a selected hearing aid is modeled and reported on the computer screen. The use of real-ear measurement continues to be an essential component of recommendations for clinical best practice but its use remains low among professionals fitting hearing aids. The utility of real-ear measurement as a tool for understanding and

resolving difficult after-fitting problems, especially related to audibility, is underappreciated. The opportunity for the patient and professional to visualize the relationship between real-world stimuli such as live speech and the instrument's gain/output settings at various input levels can be a compelling counseling tool (Mueller, 2005).

Expert Fitting Programs

In one of the few rigorous studies that specifically addressed postfitting issues, Jenstad et al. (2003) randomly surveyed audiologists who fitted hearing aids, gathering and summarizing the descriptors that their patients used in reporting common problems. The descriptions were analyzed by a pool of hearing aid researchers and seasoned dispensing audiologists who independently suggested adjustment resolutions for the fitting issues implied by the descriptors. The study showed a high degree of agreement between the experts and resulted in a series of recommended adjustments for a wide variety of specific complaints. The Jenstad et al. (2003) study forms the basis for postfitting adjustment modules found in some expert fitting programs. Replication of the original study would likely find that the authors' suggested list of issues treated in the original study has grown markedly as ever-finer variations of descriptors are gathered, and as a result a far greater number of proven, reality-based fine-tuning suggestions have emerged.

Data-Logging

Many experienced professionals place great reliance on data-logging information. Early data-logging programs (e.g., the 3M MemoryMate/Multi-Pro) merely recorded the number of hours the instruments were worn. These crude beginnings have grown to today's extensive documentation of variables including battery life, hours worn in each memory, the level and type of input signals the patient has been exposed to in each memory, the usage of directional microphones, time of exposure in different environments (e.g., quiet, noise, speech in noise, machinery noise, and wind), as well as the usage and adaptation levels of noise reduction algorithms across memories. The objective data provided can be compared to the patient's report to substantiate and understand the probable source of the issues and provide remedies. This stored information provides a far more reliable indicator and record of listening experiences than the testimony of the patient, which can be colored by faulty memory or inadequate descriptors.

Conclusion

A review of the influence and relationship of the MHA to hearing aid fitting shows that MHAs in one form or another have been a constant presence throughout the history of the electrical hearing aid. They have been used to facilitate

selection of appropriate hearing aid components, provide best estimates of required electroacoustic performance, and assist in the resolution of postfitting issues. Today's professionals are the fortunate beneficiaries of the many iterations, varieties, and configurations the MHA has taken along the way. The modern digital hearing aid and its ability to communicate with personal computers is, in many regards, the ideal embodiment of the MHA. In this model, the patient experiences amplified listening through his or her own hearing aid during the process of initial fitting and subsequent fine-tuning. The range of adjustments that can be made to modern hearing aids far surpasses those available in the early MHAs; beyond this, the realization of programming software has allowed for the introduction of numerous tools that facilitate success from the initial fitting through any subsequent fine-tuning.

Future hearing aids and assistive devices may continue to echo MHAs of the past, while taking novel form and function. For instance, patients may be given opportunity to address hearing aid fine-tuning while situated in challenging listening environments; increasingly robust processes for the fine-tuning of hearing aid parameters may be introduced; accompanied by mechanisms for detailed analysis and reporting by the patient to the professional. If the past is the father of the future, it is certain that we can look forward to innovative fitting methods that afford increased precision and enhanced patient outcomes.

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References

- Allen, J., Hall, J., & Jeng, P. (1990). Loudness growth in $\frac{1}{2}$ octave bands (LGOB)—A procedure for the assessment of loudness. *Journal of the Acoustical Society of America*, 88, 745-753.
- Arnold, T. E. (1978, Winter). How the master hearing aid can improve fittings. *Audecibel*, 130-136.
- ASHA, Reports, Number, 2. (1967, September). *A conference on hearing aid evaluation procedures* (W. E. Castle, Ed.). Washington, DC: The American Speech and Hearing Association.
- Audiotone. (1962, May). Factory certified custom fitted [Advertisement]. *National Hearing Aid Journal*, 19.
- Balbi, C. M. R. (1935). Adjusted sound amplification. *U.S. Patent No. 2,003,875*. Washington, DC: U.S. Patent and Trademark Office.

- Beattie, R. C. (1982). Comfortable speech listening levels: Effects of competition and instructions. *American Journal of Otology*, 3, 192-199.
- Benson, R. W., Davis, H., Harrison, C. E., Hirsh, I. J., Reynolds, E. G., & Silverman, S. R. (1951). C.I.D. auditory tests W-1 and W-2. *Journal of the Acoustical Society of America*, 32, 719.
- Bentler, R. A. (1991). Programmable hearing aid review. *American Journal of Audiology*, 1(5), 25-28.
- Berger, K. W. (1975). The search for a master hearing aid. In M. Pollock (Ed.), *Amplification for the hearing impaired* (pp. 305-322). New York, NY: Grune & Stratton.
- Berger, K. W. (1984). *The hearing aid: Its operation and development* (3rd ed). Livonia, MI: National Hearing Aid Society.
- Berger, K. W., Hagberg, E. N., & Rane, R. L. (1977). *Prescription of hearing aids: Rationale, procedures and results*. Kent, OH: Herald.
- Bergman, M. (1959). A master hearing aid. *ASHA*, 1, 140-141.
- Berry, G. (1939). The use and effectiveness of hearing aids. *Laryngoscope*, 49, 912-942.
- Braly, K. (1938, December). Fitting hearing aids. *Volta Review*, 777-779, 808.
- Braly, K., Utley, J., & Harris, E. (1938). Some aspects of acoustic work. *Volta Review*, 40(6).
- Briskey, R. J. (1988). The "fitting" instrument. *Hearing Instruments*, 39(3), 14, 56.
- Bunch, C. C. (1943). *Clinical audiometry*. St Louis, MO: C.V. Mosby.
- Byrne, D., & Dillon, H. (1986). The National Acoustic Laboratories' new procedure for selecting the gain and frequency response of a hearing aid. *Ear and Hearing*, 7, 257-265.
- Byrne, D., & Tonnisson, W. (1976). Selecting the gain of hearing aids for persons with sensorineural hearing impairments. *Scandinavian Audiology*, 5, 51-59.
- Carhart, R. (1946a, July). Selection of hearing aids. *Archives of Otolaryngology*, 44(1), 1-18.
- Carhart, R. (1946b, December). Tests for the selection of hearing aids. *Laryngoscope*, 56, 780-794.
- Carhart, R. (1946c). Volume control adjustment in hearing aid selection. *Laryngoscope*, 56, 510-526.
- Carhart, R. (1950). Hearing aid selection by university clinics. *Journal of Speech and Hearing Disorders*, 15, 106-113.
- Carhart, R. (1959). Evaluation of hearing aids (Abstract S-4). *ASHA*, 1, 115.
- Carhart, R. (1970). Principles of competing message speech audiometry. In *Speech audiometry* (Second Danavox Symposium; pp. 112-122). Odense, Denmark: Danavox.
- Carhart, R. (1975). Introduction. In M. Pollock (Ed.), *Amplification for the hearing impaired* (pp. xix-xxxvi). New York, NY: Grune & Stratton.
- Carter, H. A. (1943, October). Estimation of percentage of loss of hearing. *Journal of the Acoustical Society of America*, 15(2), 87-90.
- Chial, M. R., & Hayes, C. S. (1974). Hearing aid evaluation methods: Some underlying assumptions. *Journal of Speech and Hearing Disorders*, 39, 27-279.
- Christensen, L., Lee, L., & Humes, L. (1994). Can clinical word-recognition measures predict aided word recognition? *American Auditory Society Bulletin*, 19(1), 11, 16.
- Cox, R., & Studebaker, G. (1977). Spectral changes produced by earphone-cushion reproduction of hearing aid processed signals. *Journal of the American Audiological Society*, 3(1), 26-33.
- Craine, M. (1988). Master hearing aids: Their use in the fitting and sale of hearing aids. *Seminars in Hearing*, 9, 167-171.
- Crouch, J. D., & Pendry, B. L. (1975a, September). Otometry in clinical hearing aid dispensing, Part I. *Hearing Aid Journal*, 12, 42-44, 46-48.
- Crouch, J. D., & Pendry, B. L. (1975b, October). Otometry in clinical hearing aid dispensing, Part II. *Hearing Aid Journal*, 18, 31-33.
- Curran, J. R. (1972, January). A new look at sound pressure testing. *National Hearing Aid Journal*, 7, 36.
- Curran, J. R. (1974, October). Tuning in: A sound foundation for fitting hearing aids. *Hearing Instruments*, 16-17.
- Curran, J. R. (1976, May). Changing concepts in hearing aid application-1976. *Hearing Instruments*, 9-10.
- Curry, R. O. L. (1953). Method of fitting hearing aids. *U.S. Patent No. 2,625,233*. Washington, DC: U.S. Patent and Trademark Office.
- Cutler, W. H. (1975). Dispensing systems. In M. Pollock (Ed.), *Amplification for the hearing impaired* (pp. 387-424). New York, NY: Grune & Stratton.
- Davis, H., Hudgins, C. V., Marquis, R. J., Nichols, R. H., Peterson, G. E., Ross, D. A., & Stevens, S. S. (1946). The selection of hearing aids. *Laryngoscope*, 56(3, Pt 1), 85-115; (Pt 2), 135-163.
- Davis, H., & Silverman, S. R. (1960). *Hearing and deafness*. New York, NY: Holt, Rinehart & Winston.
- Davis, H., Stevens, S. S., Nichols, R. H., Hudgins, C. V., Peterson, G. E., Marquis, R. J., & Ross, D. A. (1947). *Hearing aids: An experimental study of design objectives*. Cambridge, MA: Harvard University Press.
- Day, K. M. (1940, June). Prescribing hearing aids. *Pennsylvania Medical Journal*, 43, 1299.
- Dillon, H. (2001). *Hearing aids*. New York, NY: Thieme.
- Dillon, H., Byrne, D., & Upfold, L. (1982). The reliability of speech discrimination testing in relation to hearing aid candidacy. *Journal of the Otolaryngological Society of Australia*, 5(2), 81-84.
- Dodds, E., & Harford, E. (1968). Modified earpieces and CROS for high frequency hearing losses. *Journal of Speech and hearing Disorders*, 11, 204-218.
- Duggan, W. T. (1949). Factors influencing the choice of hearing aids. *California Medicine*, 70, 198-201.
- Eberling, C. (1999). Loudness scaling revisited. *Journal of the American Academy of Audiology*, 10, 248-260.
- Elpern, B. S. (1973, September). The dispensing of hearing aids by audiologists. *Hearing Instruments*, 14-15, 18-19.
- Engelbreton, A. M., & Miller, J. D. (1982). A computer program for fitting a master hearing aid to the residual hearing characteristics of individual patients. *Journal of the Acoustical Society of America*, 12, 426-430.
- Federal Register, Part II, 40, (122). (1975). *Hearing aid industry, Proposed trade regulation rules* (Federal Trade Commission). Washington, DC: Government Printing Office.
- Final Report to the Federal Trade Commission and Proposed Trade Regulation Rule, Bureau of Consumer Protection. (1978). *Appendices C through F to the Hearing Aid Industry Staff Report* (16 CFR Pt. 440). Washington, DC: Government Printing Office.
- Fletcher, H. (1929). *Speech and hearing*. New York, NY: D. Van Nostrand.

- Fletcher, H. (1932, September). Can we scientifically advise patients as to the effectiveness of hearing aids? *Annals of Otolaryngology and Rhinology and Laryngology*, 41, 727-739.
- Fletcher, H., & Steinberg, J. C. (1929). Articulation testing methods. *Bell System Technical Journal*, 8, 806-854.
- Fogel, H. H. (1965, August). An NHAJ interview . . . Dr. Kenneth O. Johnson. *National Hearing Aid Journal*, 10-11, 22-23.
- Fogel, H. H. (1974, May). The Journal interviews . . . Kenneth O. Johnson, Ph.D. *Hearing Aid Journal*, 10, 28-32.
- Fowler, E. P. (1943a). Audiogram interpretation and the fitting of hearing aids. *Proceedings of the Royal Society of Medicine*, 36, 391-402.
- Fowler, E. P. (1943b, July). Is the threshold audiogram sufficient for determining hearing capacity? *Journal of the Audiological Society of America*, 15(1), 57-60.
- Frank, T., & Karlovich, R. S. (1976, June). Ear-canal frequency response and speech discrimination performance as a function of earmold type. *Hearing Aid Journal*, 12, 30-31.
- Franks, J. R. (1978). The master hearing aid. In P. Yanick & S. Freifeld (Eds.), *The application of signal processing concepts to hearing aids* (pp. 85-124). New York, NY: Grune & Stratton.
- Gabriel, B. (2002). Study measures user benefit of two modern hearing aid features. *Hearing Journal*, 55(5), 46, 48-50.
- Geller, D., & Margolis, R. H. (1984). Magnitude estimation of loudness I: Application to hearing aid selection. *Journal of Speech and Hearing Research*, 27, 20-27.
- Gillespie, M. E., Gillespie, M. R., & Creston, J. E., (1965, November). Clinical evaluation of a "Master Hearing Aid." *Archives of Otolaryngology*, 82, 512-517.
- Green, R., Day, S., & Bamford, J. (1989). A comparative evaluation of four hearing aid selection procedures. I—Speech discrimination measures of benefit. *British Journal of Audiology*, 23, 185-199.
- Greenbaum, W. H. (1968, March). The engineering of a master hearing aid. *National Hearing Aid Journal*, 7, 30, 32.
- Hawkins, D. B. (1992). Prescriptive approaches to selection of gain and frequency response. In H. G. Mueller, D. Hawkins, & J. L. Northern (Eds.), *Probe microphone measurements: Hearing aid selection and assessment* (pp. 91-112). San Diego, CA: Singular.
- Hayden, A. A. (1938a). Audiometers and hearing aids. *Journal of the American Medical Association*, 110, 723-725.
- Hayden, A. A. (1938b). Hearing aids from otologist's audiograms. *Journal of the American Medical Association*, 111, 592-596.
- Hayes, F., Pumford, J., & Cornelisse, L. (2012). *Evaluation of an automatic adaptation manager*. Retrieved from http://www.hearingreview.com/issues/articles/2012-09_03.asp
- Hirsh, I. J. (1952). *The measurement of hearing*. New York, NY: McGraw-Hill.
- His hobby became a nation-wide business. (1949). *Hearing Aid*, 2(11), 18-19.
- Hodgson, W., & Murdock, C. (1970). Effect of the earmold on speech intelligibility in hearing aid use. *Journal of Speech and Hearing Research*, 13, 290-291.
- Holmes, J. L. (1976, April). The master hearing aid is about to experience a renaissance. *Hearing Instruments*, 12-13.
- Holmgren, L. (1939). Hearing tests and hearing aids. *Acta Otolaryngologica*, 34(Suppl.), 1-164.
- Hudgins, C. V., Hawkins, J. E., Karlin, H. E., & Stevens, S. S. (1947, January). The development of recorded auditory tests for measuring hearing loss for speech. *Laryngoscope*, 58(1), 57-80.
- Humes, L. E. (1988). And the winner is . . . *Hearing Instruments*, 39, 24, 26.
- Humes, L. E., & Halling, D. C. (1994). Overview, rationale, and comparison of suprathreshold-based gain prescription methods. In M. Valente (Ed.), *Strategies for selecting and verifying hearing aid fittings* (pp. 19-37). New York, NY: Thieme Medical.
- Hunter, R. J. (1938). Tuning fork tests reported in terms of decibels. *Laryngoscope*, 48, 560-569.
- Hutchison, R. R. (1905). Method of determining degree of deafness. *U.S. Patent No. 789,915*. Washington, DC: U.S. Patent and Trademark Office.
- Jenstad, L. M., Van Tassel, D. J., & Ewart, C. (2003). Hearing aid troubleshooting based on patients' descriptions. *Journal of the American Academy of Audiology*, 14, 347-360.
- Jerger, J. (1999). *Audiology in the USA*. San Diego, CA: Plural.
- Jetty, A. J., & Rintelmann, W. F. (1970). Acoustic coupler effects on speech audiometric scores using a CROS hearing aid. *Journal of Speech and Hearing Research*, 13, 101-114.
- Johnson, D. O. (1976, May 10). Testimony at Federal Trade Commission. Hearings on Proposed Trade Regulation Rule for the Hearing Aid Industry, Washington, DC.
- Jones, I. H., & Knudsen, V. H. (1938). What audiometry can now mean in routine practice. *Journal of the American Medical Association*, 111, 597-604.
- Kent State University Hearing Aid Museum. (2012). *Transistor*. Retrieved from <http://www.kent.edu/ehhs/spa/museum/eras/transistor.cfm>
- Kiessling, J., Schubert, M., & Archut, A. (1996). Adaptive fitting of hearing instruments by category loudness scaling (ScalAdapt). *Scandinavian Audiology*, 25, 153-160.
- Kranz, F. W. (1928). Apparatus for aiding hearing. *U.S. Patent No. 1,679,532*. Washington, DC: U.S. Patent and Trademark Office.
- Kranz, F. W., & Rudiger, C. E. (1942, April). Relations of audiogram measures to hearing aid characteristics based on commercial experience. *Journal of the Acoustical Society of America*, 13, 363-366.
- Kuk, F. K. (1999). How flow charts can help you troubleshoot hearing aid problems. *Hearing Journal*, 52(10), 46-52.
- Langford, B. G. (1977, February). Biography of a sound pressure instrument. *Hearing Instruments*, 19-22.
- Lawrence, D. W., Halladay, H. E., & Blackledge, V. O. (1977a, February/March). Listener performance as a criterion for setting frequency selective parameters of hearing instruments. Part I. *Audiology and Hearing Education*, 26-29.
- Lawrence, D. W., Halladay, H. E., & Blackledge, V. O. (1977b, April/May). Listener performance as a criterion for setting frequency selective parameters of hearing instruments. Part II. *Audiology and Hearing Education*, 18-19, 28.
- Levitt, H., & Collins, M. J. (1980). An experimental protocol for the prescriptive fitting of a wearable master hearing aid. In G. A. Studebaker & I. Hochberg (Eds.), *Acoustical factors affecting hearing aid performance* (pp. 329-339). Baltimore, MD: University Park Press.

- Levitt, H., Neuman, A., Mills, R., & Schwander, M. (1986). A digital hearing aid. *Journal of Rehabilitation Research and Development*, 23(1), 79-87.
- Levitt, H., Sullivan, J. A., Neuman, A. C., & Rubin-Spitz, J. A. (1987). Experiments with a programmable master hearing aid. *Journal of Rehabilitation Research and Development*, 24(4), 29-54.
- Levitt, H., White, R. E. C., & Resnick, S. B. (1976). Prescriptive fitting of wearable master hearing aids: A progress report. In M. Rubin (Ed.), *Hearing aids: Current developments and concepts* (pp. 149-159). Baltimore, MD: University Park Press.
- Lybarger, S. F. (1938). Method and apparatus for selecting and prescribing audiphones. *U.S. Patent No. 2,112,560*. Washington, DC: U.S. Patent and Trademark Office.
- Lybarger, S. F. (1941). Bone conduction receiver. *U.S. Patent No. 2,230,499*. Washington, DC: U.S. Patent and Trademark Office.
- Lybarger, S. F. (1944a). Method of fitting hearing aids. *U.S. Patent Application No. 532,278*. Washington, DC: U.S. Patent and Trademark Office.
- Lybarger, S. F. (1944b). *Radioear one-half rule for maximum gain*. Canonsburg, PA: Radioear Corporation.
- Lybarger, S. F. (1947, November). Development of a new hearing aid with magnetic microphone. *Electric Manufacturing*, 40, 104-108.
- Lybarger, S. F. (1950). Wearable hearing aid with inductive pickup for telephone reception. *U.S. Patent No. 2,530,621*. Washington, DC: U.S. Patent and Trademark Office.
- Lybarger, S. F. (1951). Magnetic microphone. *U.S. Patent No. 2,552,800* (Application No. 794,146, December, 1947). Washington, DC: U.S. Patent and Trademark Office.
- Lybarger, S. F. (1957). *Radioear basic fitting procedure*. Canonburg, PA: Radioear Corporation.
- Lybarger, S. F. (1961). A new HAIC standard method of expressing hearing aid performance. *Hearing Instruments*, 11(2), 16-17, 33.
- Lybarger, S. F. (1966). Performance measurements on ear-level hearing aids. *Journal of the Audio Engineering Society*, 14(2), 126-131.
- Lybarger, S. F. (1967). Earmold acoustics. *Audicibel*, 16, 9-19.
- Lybarger, S. F. (1977). Sound leakage from vented earmolds. *Hearing Aid Journal*, 38, 28, 29, 40.
- Lybarger, S. F. (1978). Selective amplification-a review and evaluation. *Journal of the American Audiology Society*, 3, 258-266.
- Lybarger, S. F. (1980). Earmold venting as an acoustic control factor. In G. A. Studebaker & I. Hochberg (Eds.), *Acoustical factors affecting hearing aid performance* (pp. 197-217). Baltimore, MD: University Park Press.
- Lybarger, S. F. (1985). Earmolds. In J. Katz (Ed.), *Handbook of clinical audiology* (3rd ed., pp. 885-910). Baltimore, MD: Williams and Wilkins.
- Lybarger, S. F. (1988). A historical overview. In R. E. Sandlin (Ed.), *Handbook of hearing aid amplification, Volume 1: Theoretical and technical considerations* (pp. 1-29). Boston, MA: College-Hill Press.
- Lybarger, S. F., & Lybarger, E. H. (2000). A historical overview. In R. E. Sandlin (Ed.), *Textbook of hearing aid amplification* (2nd ed., pp. 1-53). San Diego, CA: Singular.
- Lybarger, S. F., & Olsen, W. O. (1983). Hearing aid measurement standards: An update and bibliography. *Hearing Journal*, 36, 19-20.
- Lybarger, S. F., Preves, D., & Olsen, W. O. (1999). A bit of history on standards for acoustical measurements of hearing aids. *American Journal of Audiology*, 8(1), 3-5.
- MacFarlane, D. (1944). Address to section on otology, College of Physicians of Philadelphia (Appendix). *Archives of Otolaryngology*, 39, 107.
- McCandless, G. A. (1988). Hearing aid formulae and their application. In R. E. Sandlin (Ed.), *Handbook of hearing aid amplification* (Vol. 1, pp. 221-238). Boston, MA: College-Hill Press.
- McCandless, G. A., & Lyregaard, P. E. (1983). Prescription of gain/output (POGO) for hearing aids. *Hearing Instruments*, 34(1), 16-21.
- McConnell, F., Silber, E. F., & McDonald, D. (1960). Test-retest consistency of clinical hearing aid tests. *Journal of Speech and Hearing Disorders*, 25, 273-280.
- Medical Research Council of Great Britain. (1947). *Hearing aids and audiometers* (Special Report No. 261. Committee of Electro Acoustics). London, UK: His Majesty's Stationery Office.
- Miller, J. D., Niemoeller, A. F., Pascoe, D., & Skinner, M. W. (1980). Integration of the electroacoustic description of hearing aids with the audiologic description of clients. In G. A. Studebaker & I. Hochberg (Eds.), *Acoustical factors affecting hearing aid performance* (pp. 355-357). Baltimore, MD: University Park Press.
- Millin, J. P. (1984). Hearing aid dispensing programs. In J. Jerger (Ed.), *Hearing disorders in adults* (pp. 146-171). San Diego, CA: College-Hill Press.
- Mueller, H. G. (1992). Individualizing the ordering of custom hearing aids. In H. G. Mueller, D. B. Hawkins, & J. L. Northern (Eds.), *Probe microphone measurements: Hearing aid selection and assessment* (pp. 183-200). San Diego, CA: Singular.
- Mueller, H. G. (1994). Update on programmable hearing aids (with an assist from Yogi Berra). *Hearing Journal*, 47(5), 13-20.
- Mueller, H. G. (2005). Probe-mic measures: Hearing aid fitting's most neglected element. *Hearing Journal*, 58(10), 21-22, 24, 26, 28, 30.
- Mueller, H. G., & Picou, E. M. (2010). Survey examines popularity of real-ear probe-microphone measures. *Hearing Journal*, 63(5), 27-32.
- Myers, E. J. (1938, October). Radio helps test hearing-aids. *Radio-Craft*, 207, 250-251.
- Mykelbust, H. R. (1943, September). The use of individual hearing aids in a residential school for the deaf. *American Annals of the Deaf*, 88, 4.
- Nelson, J. A. (2001). Fine tuning multi-channel compression hearing instruments. *Hearing Review*, 8(1), 30, 32, 34, 35, 58.
- Newhart, H., & Hartig, H. E. (1939). Hearing aids. *Archives of Otolaryngology*, 29, 614-620.
- Northern, J. L. (1992). Probe-microphone instrumentation. In H. G. Mueller, D. B. Hawkins, & J. L. Northern (Eds.), *Probe microphone measurements: Hearing aid selection and assessment* (pp. 21-39). San Diego, CA: Singular.
- Nunley, J. (1972, June). The birth of the new master hearing aid. *National Hearing Aid Journal*, 8, 26.
- Nunley, J., Staab, W., Steadman, J., Wechsler, P., & Spencer, B. (1983, October). A wearable digital hearing aid. *Hearing Journal*, 36, 29-31, 34-35.

- Olsen, W. O., & Matkin, N. P. (1991). Speech audiometry. In R. F. Rintelmann (Ed.), *Hearing assessment* (2nd ed., pp. 39-140). Needham Heights, MA: Allyn & Bacon.
- Otarion. (1962, September). Test and prescription fit at ear level. [Advertisement]. *National Hearing Aid Journal*, 6.
- Pascoe, D. P. (1975). Frequency responses of hearing aids and their effects on the speech perception of hearing-impaired subjects. *Annals of Otology, Rhinology and Laryngology*, 84(5, Suppl. 23), 1-40.
- Pascoe, D. P. (1978). An approach to hearing aid selection. *Hearing instruments*, 29(6), 12-16, 36.
- Pearson, H. A., Mundel, A., Carlisle, R. W., Knowert, W. F., & Zaret, M. E. (1946). Development of midget earphones for military use. *Journal of the Acoustical Society of America*, 18, 348-354.
- Plomp, R. (1978). Auditory handicap of hearing impairment and the limited benefit of hearing aids. *Journal of the Acoustical Society*, 65, 533-549.
- Pollock, M. C. (1975). Special applications of amplification. In M. Pollock (Ed.), *Amplification for the hearing impaired* (pp. 243-286). New York, NY: Grune & Stratton.
- Pothoven, W. J. (1948). Some aspects on modern hearing aids and their fitting, II. *Acta Otolaryngologica*, 36, 301-305.
- Preves, D. A. (1993). Flexibility in frequency response shaping and signal processing with analog hearing aids. *American Journal of Audiology*, 2(29), 29-40.
- Pumford, J., Hayes, D., & Cornellsisse, L. (2012). Automatic adaptation management: Addressing first-fit amplification considerations. *Hearing Review*. Retrieved from http://www.hearingreview.com/issues/articles/2012-03_03/asp
- Radley, W. G. (1950). The theory and engineering production of the "Medresco" hearing aid. *Acta Otolaryngologica*, 38(S 90), 54-58.
- Resnick, S. R. (1978). Master hearing aids: Past and present. *Journal of Audiological Rehabilitation Association*, 11(1), 10-20.
- Russell, R. (2012). *Sonotone Corporation history* (pp.1-8). Retrieved from <http://www.roger-russell.com/sonopg/sonopg.htm>
- Sabin, A. T., Harkies, L., Marrone, N., & Dhar, S. (2011). Weighting function-based mapping of descriptors to frequency-gain curves in listeners with hearing loss. *Ear and Hearing*, 32(20), 1-11.
- Saltzman, M. (1949). *Clinical audiology*. New York, NY: Grune & Stratton.
- Sammeth, C. A., Birman, M., & Hecox, K. E. (1989). Variability of most comfortable and uncomfortable loudness levels to speech stimuli in the hearing impaired. *Ear and Hearing*, 10(2), 94-100.
- Schwartz, D. M. (1982). Hearing aid selection methods: An enigma. In G. A. Studebaker & F. H. Bess (Eds.), *The Vanderbilt hearing-aid report* (pp. 180-187). Upper Darby, PA: Monographs in Contemporary Audiology.
- Seewald, R., & Ross, M. (1988). Amplification for young hearing-impaired children. In M. Pollock (Ed.), *Amplification for the hearing impaired* (3rd ed., pp. 213-271). Orlando, FL: Grune & Stratton.
- Seewald, R., Ross, M., & Spiro, M. (1985). Selecting amplification characteristics for young hearing-impaired children. *Ear and Hearing*, 6(1), 48-53.
- Seibel, D. (1949a). Selling sound (Part VII). *National Hearing Aid Journal*, 2(5), 8, 9.
- Seibel, D. (1949b). Selling sound (continued). *National Hearing Aid Journal*, 2(6), 21.
- Selection instrumentation/master hearing aids in review. (1988). *Hearing instruments*, 39(3), 18-20.
- Shapiro, I. (1976). Hearing aid fitting by prescription. *Audiology*, 15, 163-173.
- Shaw, E. A. G. (1974). Transformation of sound pressure from the free field to the eardrum in the horizontal plane. *Journal of the Acoustical Society of America*, 56, 1848-1861.
- Sheets, B. V., & Hedgecock, L. D. (1949). Hearing aid amplification for optimum speech reproduction. *Journal of Speech and Hearing Disorders*, 14, 373-379.
- Shore, I., Bilger, R. C., & Hirsh, I. J. (1960). Hearing aid evaluation: Reliability of repeated measurements. *Journal of Speech and Hearing Disorders*, 25, 152-170.
- Skafto, M. D. (1990). Fifty years of hearing health care, 1940-1990. *Hearing Instruments*, 41(9), 1-130.
- Skinner, M. W., Karstaedt, M. M., & Miller, J. D. (1982). Amplification bandwidth and speech intelligibility for two listeners with sensorineural hearing loss. *Audiology*, 21, 251-268.
- Sound pressure instruments. (1977, February). A review of what is on the market today. *Hearing Instruments*, 17-19.
- Staab, W. J. (1990). Digital/programmable hearing aids—An eye toward the future. *British Journal of Audiology*, 24, 243-256.
- Staab, W. J. (2000). Hearing aid selection: An overview. In R. E. Sandlin (Ed.), *Textbook of hearing aid amplification* (2nd ed., pp. 55-135). San Diego, CA: Singular.
- Stearns, W. P., Blackledge, V. O., & Rohrer, J. S. (1974). *Prosthetic device for providing corrections of auditory deficiencies in aurally handicapped persons*. U.S. Patent No. 3,818,149. Washington, DC: U.S. Patent and Trademark Office.
- Stearns, W. P., & Elpern, B. S. (1974). Method of fitting a prosthetic device for providing corrections of auditory deficiencies in aurally handicapped persons. *U.S. Patent No. 3,848,091*. Washington, DC: U.S. Patent and Trademark Office.
- Stearns, W. P., & Lauchner, J. K. (1974). Apparatus and prosthetic device for providing electronic correction of auditory deficiencies for aurally handicapped persons. *U.S. Patent No. 3,784,750*. Washington, DC: U.S. Patent and Trademark Office.
- Stearns, W. P., Lawrence, D. W., & Rohrer, J. S. (1979). New quantitative measurement techniques for fitting hearing aids. *Hearing Instruments*, 30(8), 14, 44.
- Strommen, E. (1946). Fitting hearing aid device. *U.S. Patent No. 2,394,569*. Washington, DC: U.S. Patent and Trademark Office.
- Studebaker, G. A. (1982). Hearing aid selection: An overview. In G. A. Studebaker & F. H. Bess (Eds.), *The Vanderbilt hearing-aid report* (pp. 147-155). Upper Darby, PA: Monographs in Contemporary Audiology.
- Studebaker, G. A., & Hochberg, I. (1980). Preface. In G. A. Studebaker & I. Hochberg (Eds.), *Acoustical factors affecting hearing aid performance* (pp. xii-xiv). Baltimore, MD: University Park Press.
- Stutz, R. (1968, March). Whatever happened to the master hearing aid? *National Hearing Aid Journal*, 8, 28.

- Sung, G. S., Sung, R. J., & Angellelli, R. M. (1971). Effect of frequency response characteristics of hearing aids on speech intelligibility in noise. *Journal of Auditory Research*, 11, 318-321.
- Thomas, I. B., & Pfannbecker, G. B. (1974). Effects of spectral weighing of speech in hearing impaired subjects. *Journal of the Audio Engineering Society*, 22, 690-693.
- Traynor, R. M. (1997). Prescriptive procedures. In H. Tobin (Ed.), *Practical hearing aid selection and fittings* (pp. 59-74). Baltimore, MD: Scientific and Technical Publications Division, Department of Veterans Affairs.
- Tumarkin, A. (1935). Scientific audiometry and selective amplification in the design and construction of modern deaf aids. *Journal of Laryngology and Otology*, 50, 834.
- Valente, M., & Van Vliet, D. (1997). The independent hearing aid fitting forum (IHAF) protocol. *Trends in Amplification*, 2(1), 6-35.
- Valentine, S., Dundas, J. A., & Fitz, K. (2011). Evidence for the use of a new patient-centered fitting tool. *Hearing Review*, 18(4), 28-34.
- Vicon. (1962, July). The finest in hearing instrumentation for your most important clients [Advertisement]. *National Hearing Aid Journal*. (inside back cover)
- Victoreen, J. A. (1968). Method and apparatus for testing hearing. *U.S. Patent No. 3,408,460*. Washington, DC: U.S. Patent and Trademark Office.
- Victoreen, J. A. (1973). *Basic principles of otometry*. Springfield, IL: Charles Thomas.
- Victoreen, J. A. (1974). Equal loudness pressures determined with a decaying oscillatory waveform. *Journal of the Acoustical Society of America*, 55, 309-312.
- Viehwig, S. H. (1978, August). Use of a master hearing aid in clinical hearing aid evaluation procedures. *Hearing Instruments*, 22, 26, 28, 31, 47.
- Viewpoint. (1976, December). The evolving hearing aid dispensing program. *Hearing Instruments*, 22-23, 38.
- Voroba, B. (1984). A tool for the optimization of hearing aid fittings. *Hearing Instruments*, 35(1), 12-14, 16.
- Voroba, B., & Oberlander, D. A. (1989). Mass production auditory canal hearing aid. *U.S. Patent No. 4, 870,688*. Washington, DC: U.S. Patent and Trademark Office.
- Voroba, B., & Wilkinson, J. P. (1988a). Patient controlled master hearing aid. *U.S. Patent No. 4,759,070*. Washington, DC: U.S. Patent and Trademark Office.
- Voroba, B., & Wilkinson, J. P. (1988b). Master hearing aid test console. *U.S. Patent No. D299,058*. Washington, DC: U.S. Patent and Trademark Office.
- Voroba, B., & Wilkinson, J. P. (1988c). Master hearing aid patient console. *U.S. Patent No. D299,059*. Washington, DC: U.S. Patent and Trademark Office.
- Walden, B. E., Schwartz, D. M., Williams, D. L., Holum-Hardeggen, L., & Crowley, J. (1983). Test of the assumptions underlying comparative hearing aid evaluations. *Journal of Speech and Hearing Disorders*, 48, 264-273.
- Watson, L. A. (1944, October). Certain fundamental principles in prescribing and fitting hearing aids. *Laryngoscope*, 54, 531-558.
- Watson, L. A., & Tolan, T. (1949). *Hearing tests and hearing instruments*. Baltimore, MD: Williams and Wilkins.
- Watson, N., & Knudsen, V. O. (1940). Selective amplification in hearing aids. *Journal of the Acoustical Society of America*, 11, 406-419.
- Weille, F. L., & Billings, B. H. (1937, May 6). The study of the efficiency of carbon microphone hearing aids. *New England Journal of Medicine*, 216, 790-794.
- Welch, C. (1988). Principles and clinical applications of otometry. *Seminars in Hearing*, 9(3), 197-204.
- Wells, W. A. (1938). The facts and fallacies of hearing tests. *Laryngoscope*, 48, 137-145.
- Wengel, A. M. (1940a). Hearing aid device. *U.S. Patent No. 2,192,669* (Application No. 129,514, March 6, 1937). Washington, DC: U.S. Patent and Trademark Office.
- Wengel, A. M. (1940b). Method and apparatus for testing hearing. *U.S. Patent No. 2,217,394*. Washington, DC: U.S. Patent and Trademark Office.
- Zelnick, E. (1987). Review of suggested hearing aid procedures. In E. Zelnick (Ed.), *Hearing instrument selection and evaluation* (pp. 1-33). Livonia, MI: National Institute for Hearing Instrument Studies.