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Historical Article

History of the technological development of air conduction hearing aids

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Abstract
This was a study of the history of the technological development of air conduction hearing aids, and a review of international literature on the subject. The technological evolution of amplification devices, from their origin to the present day, can be divided into seven distinct periods: the period of sound collectors, the period of hearing devices constructed from carbon, the period of vacuum tubes, the transistor period, the period of integrated circuits, the microprocessor period and the period of digital hearing instruments. Throughout these different stages, hearing instruments have progressively developed reaching their present state.

The current era is itself undergoing constant development and change. With the introduction of new technologies, we expect that the rate of change will increase rapidly in the future.

Key words: History of medicine; Hearing aids

Introduction

The communication difficulties associated with an auditory deficiency have always preoccupied man. Many diverse devices have been used to try to compensate for auditory handicaps. The attempt to amplify sound selectively has been common in all of these devices. In fact, even at present, a hearing aid is a miniature amplification system where the gain for each frequency (from 250 to 5000 Hz) is proportional to the hearing deficiency. The technological evolution of hearing aids, from their conception to present day may be separated into two primary eras,[1] which can be further subdivided into seven periods (Table I).[2] This evolution has been linked less to advancements in the knowledge of the physiology of hearing than to the progression of electronics and physical acoustics. The role of an amplification device is to amplify acoustic pressure for the impaired auditory system.[3] Each period has attempted to achieve this goal in unique ways.

Sound collector period

Aside from the natural gesture that man makes of placing his ‘hand in the shape of a trumpet’ behind his ear in order to better direct sound waves into his ear canal,[4] one may consider the trumpet made of horn as the most ancient acoustic amplifying device. This method has been used from the beginning of time by hunters and warriors. It is quite probable that deaf people of ancient times and the middle ages must have thought of placing the mouthpiece of a horn or a bugle to their ear for purposes of amplification.[5]

Athanasius Kircher was the first to write an essay on the hearing aid, and this was published in 1673. It is here that he described the famous Ellipsis otica, considered as the first acoustic prosthesis.[6] The XVIIIth and XIXth centuries saw a plethora of inventions of shells, ear trumpets, and various kinds of resonators (Figure 1).[7,8]

TABLE I
PERIODS OF TECHNOLOGICAL EVOLUTION OF HEARING AIDS

I. *Acoustic era*
   (1) Sound collectors
II. *Electronic era*
   (2) Carbon devices
   (3) Vacuum tube
   (4) Transistors
   (5) Integrated circuit
   (6) Microprocessor
   (7) Digital technology

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FIG. 1
Ear trumpet.

In trumpets, the modification of the signal is due to the increase of the flow of acoustic energy relative to the difference in diameter between the opening at the entry and the exit (large at the entry and small at the exit). Another factor affecting sound amplification was the resonance of the air column contained within the instrument.[9] Two observations are apparent concerning the construction of these acoustic amplifiers: the need to conceal them and the desire to maintain the helicoidal shape of the human cochlea as much as possible.

Sound collectors can be divided into three classes according to their construction (Table II).[10,11] This period ended at the beginning of the XXth century with the invention of the first electrical hearing aid.

Period of electronic hearing devices constructed from carbon

The invention of the carbon transmitter by Blake and Hughes in 1878 gave Alexander Graham Bell's telephone, developed in 1876, the necessary means for its adaptation as an acoustic prothesis.[12] The first telephone was a transformer of sound (acoustic waves) to electricity (electric waves) with a sound transducer at the other extremity of a wire that transmitted the sound. The system functioned by conducting an electric current, produced by battery, through carbon granules contained in the cavity of a microphone where one of the walls was a diaphragm or a vibrating sheet. It was this diaphragm that was displaced by the sound wave by compressing and decompressing the carbon granules, which in turn changed their resistance with the flow of electrical current (alternating current) in relation to the acoustic pressure applied on the granules by the diaphragm. The variations of the electrical signal reached the magnetic receiver, which transformed this electrical energy into sound waves. Thus the hearing aid went from being passive to active. Bell explained his discovery in the following way: 'I was struck by the fact that the bones of the human ear are very big, when compared with the fine, delicate membrane which makes them work, and the idea came to me that, if a membrane this delicate could move these fairly big bones, why would not a thicker more solid membrane be capable of moving my piece of steel? Hence, this is how I imaged the telephone'.[13]

TABLE II
CLASSES OF SOUND COLLECTORS

I.	Instruments fitted into the ear or on the auricule
II.	Handheld instruments
III.	Acoustic tubes

Two names are associated with the production of the first electrical amplifier for the deaf: Ferdinand Alt, of the Politzer Clinic in Vienna in 1906 and Miller Reeve Hutchinson in the USA in 1902. It was the beginning of the analog era, which was to bring together two important physical principles – sound waves and electrical vibrations, the receiver and microphone. The first auditory prosthesis consisted of a receiver or a carbon pellet microphone and an earphone of the magnetic telephone type (the alternating electrical current resulted in the variation of the magnetism in the magnet placed within the earphone causing different pressures on the diaphragm that reproduced the sounds received). The linear amplification occurred in the receiver itself. This system, with two distinct elements, was powered by a large carbon-zinc liquid battery, worn separately. It was a system that was not routinely used.[14]

In 1925, Sell, of Siemens, invented the first carbon amplifier separate from the microphone placed in the hearing aid. This amplifier was in fact a magnetic receiver coupled to a carbon microphone with a common diaphragm powered by the same battery supplying the current for amplification. At this point, the hearing aid consisted of four elements: the carbon microphone, the carbon amplifier, the receiver and the battery (Figure 2). This basic structure remains basically unchanged even today.

Vacuum tube period

The electrical tube 'under vacuum' was invented by Lee DeForest in 1906 and was rapidly adapted for radio and telephone devices. In 1883, Thomas Edison introduced a second electrode into his final experiments on the incandescent lamp. Thus, he

FIG. 2
Carbon hearing aid.

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discovered that an unexplained current passed in an unidirectional manner between the two electrodes, this effect he called the 'thermo-ionic' effect. This fundamental discovery was not really put to good use until 1906 when DeForest, who by introducing a third electrode into the vacuum tube, opened the door to a new electronic era. This third electrode (the grid) allowed the current emitted by the source of electrons to be controlled and enabled amplification and oscillations to occur. It was not until 1920 that Earl Hanson of Boston developed the first hearing aid with an electric tube as an amplifier.[15] It was produced by the Western Electric Company and distributed by the Globe Phone Company in 1921. It also had a carbon microphone. This amplification system was better than the carbon system; however, it was initially much heavier.

In 1936, Sawyer introduced the salt crystal microphone, whose property was to produce an electrical current when it was bent or slightly inclined in certain directions. The current produced was proportional to the mechanical force; this 'piezo-electric' effect transformed the mechanical sound vibrations into electrical current. Nineteen forty-six saw the introduction of the magnetic microphone (the opposite system to the magnetic receiver). At the same time, batteries underwent an important evolution decreasing in size with the use of mercury instead of zinc. The reduction in size allowed for practically all of the elements of the prosthesis to be placed in the same housing, with the exception of the receiver. The receiver, more often magnetic, had become small enough to be placed directly in the ear by means of a custom earmould. It was linked to the housing by a conducting wire.

Progressively systems for the control of output by peak clipping (limitation of the maximum level of output: PC = peak clipping) and compression (AGC = automatic gain control) were adapted for use in hearing aids. Numerous prosthetic models appeared on the market[16] and with the arrival of the first manufacturing facilities, hearing aid dispensing made its real beginning. The potentiometer was also progressively introduced into hearing aids giving the fitter more flexibility in the regulation of the amplification level.

Transistor period

The invention of the transistor was the result of 20 years of research in the Physics of Solids (1920 to 1940). In 1947, three researchers from Bell Telephone Laboratories, William Shockley, John Bardeen and Walter Brattain, perfected the transistor. For the first time, the signals inside a semi-conductor were suitably amplified because of the passage of an electrical current between two gold electrodes placed on a piece of germanium. Apart from amplification, the transistor was capable of generating signals, and of modulating and even transforming them therefore needing only one battery. The variable efficiency of this first system was improved in 1951 by Shockley. He managed to obtain more reliable amplification. By varying the mounting of the transistors in the hearing aid, one could vary the amplification and impedance (the total effective resistance of an electric circuit to alternating current).

FIG. 3
Behind the ear hearing aid.

From 1952, the transistor rapidly replaced the electric tubes, whose performance was markedly inferior. The process of conduction had become electronic and no longer ionic. Because a semi-conductor, the size of a small piece of metal without vacuum or tube surrounding it, needs only a continuous low voltage power supply, it was possible to achieve miniaturization of the electronic components and incorporate the receiver into the instrument's housing. As a result, the weight of the hearing instrument was reduced from 550 g in 1941 to less than 5 g in 1980.[17] It could at last be worn behind the ear (1955, Viennatone) (Figure 3), and by 1962, in the ear (Audivox) (Figure 4). While the internal noise of the hearing aid could be gradually reduced with this new technology, feedback problems increased significantly. This was because the microphone and the receiver were not much closer to each other as a result of the miniaturization process.

The development of the transistor allowed for the further development of the amplifier characterized by its power (acoustic gain and maximal power output (MPO)) and by its frequency response. The

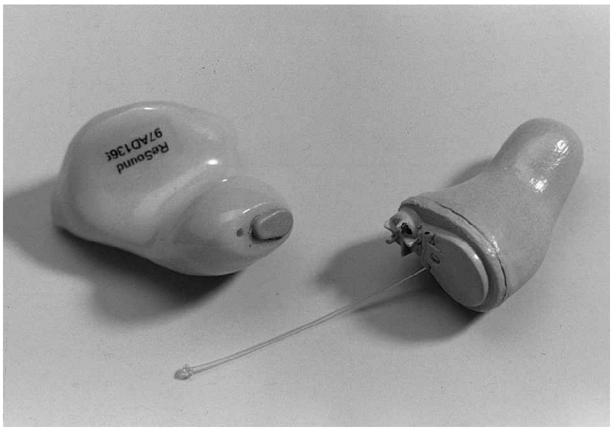

FIG. 4
In the ear hearing aid.

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acoustic gain may be modified by a potentiometer and in this way can be individually adapted to the needs of the user. Adjunction of systems of compression and symmetrical peak clipping allow for a variation in the maximum level of the output and to avoid exceeding uncomfortable levels.

Period of integrated circuits

The first integrated circuit developed by Jean Hoerni of the Fairchild Semiconductor's factory and by Robert Noyce in 1958 replaced transistors, resistors and other capacitors, which progressively disappeared. Thus, the amplifier became an assembly of different integrated circuits. In 1964, Zenith used an integrated circuit in a hearing instrument for the first time. Before the introduction of integrated circuits, the multiple wires and soldering points between the different elements of the amplifier were frequently the cause of breakdowns and complications. Further miniaturization was therefore not possible. Integrated circuits solved many of these problems.

The ceramic microphone was introduced in 1967 and was later replaced by the electret microphone (dielectric with a permanent polarization) in 1971. These microphones allowed an increase of the frequency range of hearing aids.

The zinc-air battery made its appearance in 1977. This battery, which is mercury free, has a higher capacity than the mercury battery because of the greater volume of the anode. At the same time, the evolution of integrated circuits was continuing with the use of new materials such as gallium. The development of the amplifier is linked to the integrated circuit, which allows a multiplication by a constant of the initial sound intensity. One can distinguish four principal classes of amplifier function (Class A, B, C and D) by varying the time and the rating of the conduction of the active elements (Table III). The amplification is controlled by additional circuits (as such the automatic gain control circuit) that enhance the functioning of the amplifier.

The principle of these systems is that each time an input signal reaches a pre-determined intensity value, the amplification stops being linear and the signal is compressed, thus automatically and temporarily reducing gain. The time needed for the system to respond to the increase in input is the attack time. The time during which the gain limitation is active is the activation time, and the time necessary for the initial amplification conditions to be re-established is the return or recovery time.[18] Even though the recovery time could be adapted for a particular situation, it is often either too long, or too short depending on the listening environment.

TABLE III
CLASSES OF AMPLIFICATION SYSTEMS

A.	Linear amplification
B.	Non-linear amplification type push-pull
C.	Non-linear amplification type push-pull ameliorated
D.	Digitalized, non-linear amplification

For this reason, certain hearing instrument manufacturers have introduced recovery times that are adaptive.[19]

The amplifier is almost always associated with filtering systems of tone controls that allow the adaptation of the response of the hearing instrument to the individual hearing loss. The filter may be passive or active. The passive filter can affect the frequency response in either the low or high frequency region, over a limited frequency range. An active filter affects the same frequency region but over a larger frequency range allowing creation of steeper filters. The switched capacitor filter = SWP developed by Bernafon in 1987 is a good example of an active filter. The regulation of the filters may be done manually (trimmer) or by computer (digitally programmable hearing aids).

Microprocessor period

Invented in 1971 by Edward Hoff, the microprocessor enabled the significant miniaturization of logical functions in electronic equipment and corresponded with a universally programmable integrated circuit. Microprocessors were used in hearing aids from the end of the 1980s, allowing them to be programmed and to use different amplification channels. The first models of digitally programmable hearing instruments were introduced by Bernafon in 1987 and Widex in 1988. In these instruments, at least one part of the amplifier settings was no longer carried out by adjustment of metallic components, but by means of digital circuits.[20] This digitalization of the settings did not fundamentally change the function of the hearing instrument, as the amplification circuits and the correction of the input signal remained analog (for example, hybrid technology based on the zeta noise blocker).[21]

New strategies were developed to try to solve problems of understanding speech in background noise. In 1995, multi-microphone technology 'AudioZoom', which incorporated the functionality of classic omnidirectional microphones (captivation of sound input from all directions). Directional microphones had been used previously to achieve noise reduction. The newer strategies allowed electronic switching between two microphone settings with the use of a remote control.[22,23] This technology, developed by Phonak, introduced a new milestone in noise reduction and optimalization of speech intelligibility in adverse listening environments.[24] The classical directional microphone, which had already been introduced in the 1970s, was not a new type of microphone. It functions by capturing sound energy from the rear and the sides at a membrane that attenuates it in relation to sound originating from the front.[25,26] This system allows for a significant improvement in speech intelligibility in noise when the signal of interest comes from the front.

The introduction of microprocessors also allowed compression circuitry to become dynamic and increased the number of available compression channels allowing more sophisticated control of

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nonlinear amplification. Originally developed by Villchur[27] and AT & T Bell Laboratories around the middle of the 1980s, the whole dynamic range multiband compressor[28] allowed the separate treatment of low and high frequency sounds at different intensity levels. This system, taken over by the Resound Corporation, was introduced to the market for the first time in 1990. The system efficiently compensated for the recruitment phenomenon.[29,30] This new technique (called 'Cochlea dynamics' by Resound) revolutionized hearing instruments, and some form of wide dynamic range compression is now available from all major manufacturers.

Period of digital hearing instruments

It was in 1979 with the introduction of the compact disc that the digitalization of sound really took off. Analog signal processing results in distortions at each level of its treatment. Digital technology codes and simplifies the signal with the aim of keeping it intact at each level. That then allows the conservation of the input signal regardless of the applied processing.[31] The digital information thus obtained may be treated to achieve the desired results. Ludwig Moser of Würzburg appears to have been the first to have described the use of digital signal processing for a hearing instrument.[32]

Digital hearing instruments are composed of two elements in addition to the microphone, amplifier and receiver. They are an analog-to-digital converter before the amplifier, and a digital-to-analog converter before the receiver. By using microprocessors, these different elements may overlap. Widex's Senso, introduced in 1996, was the first fully digital hearing aid to have been successfully commercialized. The very first digital hearing instrument was introduced by Nicolet in 1987. It was a body type instrument that had been produced in a limited series, but it never extended beyond the experimental stage. A second digital hearing instrument was presented by Danavox in 1992 for certain types of profound impairment.[33,34] The Danavox was not really a fully digital instrument but the first hearing aid to incorporate digital signal processing. The feedback suppression circuitry was fully digital, the rest of the hearing instrument was analog.

Digitalization offers many possibilities for signal processing such as spectral and temporal analysis of the signal, selective amplification, frequency attenuation, localized filters, reduction of background noise, adjustments for dynamic range and feedback suppression. These are possibilities that are not yet fully optimized, and the rate at which innovations are introduced into the market is growing rapidly. For example, in 1997, Siemens presented the first digital instrument using dual microphone technology.[35]

Digitalization of signal processing will not, in the short term, solve all of the problems encountered in hearing instrument design. Numerous companies concentrate their effects on the research and development of new technologies associated with digitalization and the perfection of the principle problems associated with hearing aids. The distortion of the signal and recruitment, noise reduction, the loss of the open ear canal resonance, feedback, the occlusion effect, and the internal noise of microphones are the main difficulties to overcome. Three principal axes of development can be seen: the perfection of electronic signal processing, implantable hearing instruments[36,37] and systems using wireless FM transmission.

The future is certainly with the supra-conducting materials (solid materials characterized by their electrical non resistance). These would allow for the elimination of all dissipation of energy and at the same time increase the output of the electronic device, as well as the length of time energy can be stored. Even if adapted to its optimum, a hearing aid may never be capable of restoring normal audition. In sensorineural hearing loss, the ear produces distortions and even if the hearing instrument can make sounds audible, it cannot give 'the same auditory impression as a normal hearing ear does'.[38] One day perhaps we will see an 'intelligent' hearing aid that will use the natural inter-auricular space and that will analyse the content of the message with the aim of perfecting the relation between the signal and sound.

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