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Binaural Recording Technology: A Historical Review and Possible Future Developments

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Summary
The facsimile or true-to-original reproduction of sound events is of great interest in acoustics and related areas and has been researched for many years. One form of achieving this is binaural technology. Many consider binaural technology a very modern technology and some even consider that it is strictly related to and was invented for sound quality research. However, binaural technology, especially recording technology, has been established for some time and, in fact, the first steps were made in around 1880. Over the decades this technology has made enormous advances, due to the dedication of many people, but some challenges related to achieving a true facsimile are still to be resolved. The most important milestones and also the remaining challenges are presented herein and the prospects for the near future are discussed.

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1. Introduction

Recording and reproduction of sound signals in such a way that the sound event is restored entirely has always been of special interest to people engaged in the recording, transmission and reproduction of sound. To achieve this objective several techniques have been developed, including stereophonic techniques and binaural recording and reproduction techniques. The latter are also known as head-related stereophony or dummy-head technology.

Within the last few years, interest in binaural recording and reproduction have increased once again, due to advances in auralization and also the popularization of the Internet, where users can find a large number of binaural recordings or simulations. Many of these websites, nearly all commercial publications and even some published conference papers, give the impression that binaural technology, especially manikins and artificial heads, are relatively recent inventions. However, attempts to obtain signals and reproduce true-to-original sound have been made for over 100 years, and many people have spent considerable effort on the development of the technology.

This article will review some important milestones in the development of manikins and artificial heads and will give a brief outlook of possible future developments.

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2. On the understanding of binaural hearing and technology

Due to the nature of this article, which is a historical review, a short note should be given on early research into binaural hearing and about the term binaural itself. According to Wade and Deutsch [1], who compiled a comprehensive review of early research into binaural hearing, the work of Wells in 1792 and Venturi in 1796 were probably the first studies ever on the topic of binaural hearing. During the nineteenth century and at the beginning of the twentieth century other researchers dealt with binaural hearing, such as Wheatstone [2], Dove [3, 4], Seebeck [5], Alison, Steinhauser [6], Thompson [7, 8, 9] and J. W. Strutt (Lord Rayleigh) [10]). They largely agreed that the presence of two sound receivers, the ears, is responsible for a large portion of the sophistication of human sound perception, enabling localization and distance perception of sound sources[1].

The term binaural itself was, according to Wade and Deutsch [1], coined by Alison in 1861 to describe that two ears are involved in human hearing. Accordingly, the term was often used until the 1970s for techniques that recorded or reproduced two signals destined for the two ears[2], not necessarily to describe signals that have been modified by the human body, and would therefore correspond to the signals at the eardrum of a listener. Also, the

[1] Other important binaural effects such as the cocktail-party effect and the precedence effect (Haas-effect) were discovered later.

[2] Kinns misused the term binaural even in the title of a paper on beamforming using two closely spaced microphones [11].

term does not necessarily describe techniques that modify the signals similarly. Consequently, systems that delivered two-channel sound were called binaural, as well as stereophonic, the latter term probably being coined in the 1880s. Bell may have been the first to have mixed up the two terms when he wrote about “stereophonic phenomena of binaural audition” [12]. Bell understood stereo as being related to the spatial impression provided by hearing with two ears (binaural). Also, Blumlein’s famous patent on stereo [13] used the term binaural in its description. Fletcher, in the 1920s, may have been the first to use the term binaural for a recording technique and Hammer and Snow [14] were probably the first to distinguish between binaural and stereophonic pick-up. They considered a system fully binaural when the signals acquired with a dummy head (e.g. “Oscar”) were reproduced by headphones. Systems that do not comply with this requirement were then called stereophonic. The terms “dummy (head)” or “artificial head” were also already used in the 1920s [15, 16]. At the end of the 1930s De Boer and Vermeulen introduced the German term “*Kunstkopf*” [17], a term that was also adopted by English-speaking authors. In the 1950s Snow [18] also gave distinctive definitions for binaural and stereophonic sound pick-up, but considered the imprecise definition of terms a common phenomenon in new developments.

The distinctive definition of Hammer and Snow or the terms coined by Fletcher, Firestone, and DeBoer and Vermeulen were not generally adopted and until the 1970s the terms binaural and stereophonic were used mostly as synonyms.

Later mixed terms such as “binaural stereophony”, “dummy head stereo(phony)”, “head-related stereo(phony)” or “*Kunstkopfstereophonie*” were also created.

Today the term binaural technology is used to describe the fact that two signals are obtained, stored or reproduced in such a way that the signals correspond to the sound signals that would be found at the eardrum of a listener, or another well-defined reference point in the ear canal, after being modified by the human body. By obtaining and reproducing these signals the auditory event can be reproduced as closely as possible, that is, the signal is true-to-original.

3. Initial steps: From pairwise microphones to the first manikin

In order to provide better audio transmissions of opera pieces, experiments with several pairs of spaced microphones started as early as 1881 when Ader filed a patent on “Improvements of a telephone equipment in theatres”. The same year, under his guidance, the first wire transmission of paired microphone signals from the Paris opera house to rooms in the *Palais* of the Paris Electrical Exposition more than two kilometers away were carried out [19, 20, 21, 22, 23, 24]. The same pick-up systems were also during the Paris Electrical Exposition of 1881, installed in *L’opera comique* and *Le têâtre Français* [20].

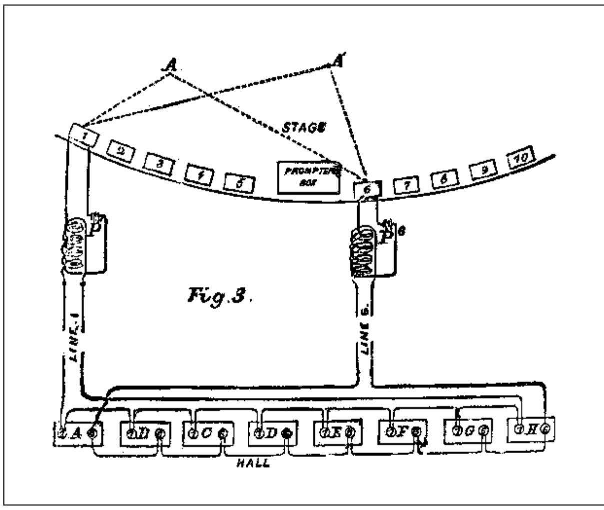

Figure 1. Diagram of the microphone and transmission set-up used for the first documented stereophonic transmission by Clément Ader in 1881, after [19].

The pick-up consisted of multiple carbon pencil microphones, placed pairwise on the stage. The signals were transmitted pairwise (Figure 1) to be reproduced with monaural headphones, typical of early telephones, one for each ear.

Hospitalier [19] compared Ader’s invention with stereoscopy, but did not coin the term stereophony[3]. Later the invention was named *théâtrophone* in France and electrophone elsewhere, and it was used commercially until 1932.[4]

Genuit, Gierlich and Bray [27] as well as Stahl [28] maintain that as early as 1886 artificial heads were used in the Bell laboratories. Nevertheless, the author of the present article can not confirm this fact, and it should be noted that, in fact, Bell Laboratories as a research institution of this name came into existence only on 1st of January 1925 when WE Engineering and AT&T Engineering formed the Bell Telephone Laboratories.[5] Also one should bear in mind that the microphones available in 1886, see Beranek [29][6] for short overview of early microphone developments, would hardly fit into an artificial head. If one assumes instead that the signals were captured without microphones and transmitted using tubes, then such an artifical head would have been possible. The fact that humans can localize sound sources using their binaural hearing ca-

[3] There are some sources that affirm that the English term stereophonic was first used by Western Electric Inc.

[4] For more information on Ader’s invention and its commercial use see e.g [22, 25, 23].

[5] Also, Jont B. Allen, formerly at Bell Labs., and Gary Elko stated in a personal communication that they were not aware of the fact that a manikin had been used before the 1920s. Jont B. Allen is aware that in around 1920/21 Goehner made the first artificial head for a stereo system and that Alexander Graham Bell came to the labs to see it. Unfortunately, Lucent Technologies, which incorporated the former Bell Labs., did not respond to a request for access to the historical archives of Bell Labs.

[6] See also some corrections and comments made by Miessner [30].

pabilities was used as early as in World War I, for localization of both aircraft and submarines. Johnson and Dugeon [31] described aircraft localization equipment consisting of two arrays of acoustic receivers. The sound captured by any of the two arrays was transmitted by a tubular waveguide to one ear of the operator. A similar invention using two hydrophones was used to localize submarines [32].

At the beginning of the 1920s Harvey Fletcher[7], who dedicated many years of his scientific research to the hard of hearing, developed a "binaural" hearing aid to be used by Alfred DuPont, a member of the famous DuPont family, which had a history of hearing loss in the family, in his board meetings [33]. Two microphones were placed on the board meeting table and connected via tube-amplifiers to a headphone. A similar, if not the same, system was patented in 1927 by Fletcher and Sivian (Figure 2), on behalf of Western Electric, as a "binaural" telephone system [15]. According to the application, two microphones are placed flush with the wall of a balloon made of leather or cloth and packed with sponge rubber, wool or cotton. In this way, three elements effecting the sound transmission from a sound source to the eardrum of a listener were modelled to some degree: separation of the receivers, shadowing and absorption.

Also in 1921, Doolittle filed a patent, finally granted in 1931, for an apparatus to obtain, store and reproduce two-channel sound [34] in order to allow for localization of the sound event in space when heard. After the application the sound was captured using two microphones but no acoustic septum was present. Thus, the invention was similar to those of Ader adding the storage of the signals. In 1924 Doolittle obtained another patent for the transmission of two channels via radio [35]. In the same year his radio station WPAJ[8] obtained permission to broadcast at two different frequencies [9]. In this way, with two radios, each receiving one channel, one could hear the complete "binaural" transmission.

Usually headphones were used at this time as the use of loudspeakers was only just starting.

According to an article written by Doolittle in 1925 and named "*Binaural Broadcasting*" [36] and the information given by Sherman [37] one must conclude that the broadcasting was not binaural in the sense in which binaural is understood today, as no model of a head, nor a baffle, was used. Therefore, the information given by Ericson and colleagues [38] regarding the supposed "binaural radio transmission" is not to be understood as binaural in the sense that binaural is understood herein. The same very probably applies to Ericson's statement that the Berlin opera house used "binaural transmission" in around 1925.

[7] Fletcher had been a member of staff of the Research Division of Western Electric Engineering Dept since 1916.

[8] From spring 1925 the station was called WDRC as one can see at http://www.wdrcobg.com/history.html.

[9] See also http://www.wdrcobg.com/doolittle2.html and the information on the 16th of august 1924 at http://www.wdrcobg.com/history.html

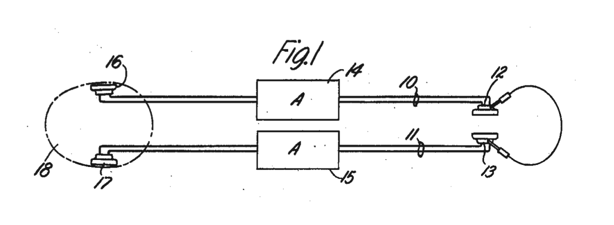

Figure 2. The "binaural" telephone system after Fletcher and Sivian [15].

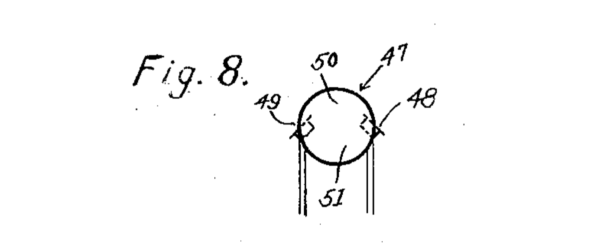

Figure 3. The "artificial head" patented by W. Bartlett Jones [39].

In 1927, W. Bartlett Jones filed a patent for devices to capture, record and reproduce "binaural" signals. The application is not very detailed, but considers a type of "artificial head" represented by a sphere. Microphones placed on the sphere are directed forward, as shown in Figure 3, which after application should simulate the orientation of human pinnae.

The first original sources available to the author of the current review that relate to the use of a manikin as a device for capturing sound are from around 1928 to 1930 and were published by Firestone [40, 16]. He describes the use of a manikin which imitated a human head made of wax and a torso made of wood. The receivers were Baldwin receivers, placed where the ears of the manikin would be. The manikin was then used to investigate phase and intensity differences at the two microphones.

Also, in the 1930s new experiments were carried out with manikins at Bell Labs. According to Fletcher, head of acoustical research at this time, the group worked on the improvement of the telephone transmission of the human voice, but were inhibited by the low fidelity [41, 42]. Based on Fletcher's experience with his "binaural" hearing aid (Figure 2) and his knowledge that having two ears provides higher fidelity in relation to the sounds perceived, the group started to capture the signals using a manikin [33, 41, 43]. The manikin, named "Oscar", was made using a manikin bought from a wax figure dealer and had microphones mounted on the cheeks, just in front of the ears[10] as shown in Figure 4 [14]. The construction of "Oscar" as well as the efforts undertaken for calibration and equalization of the binaural signals were described in de-

[10] Some sources maintain that the microphones were in the ears [33], whereas others report that the microphones were at the position of the ears [44], and others even maintain that they were only close to the ears [14, 45, 38, 46] as one can see in Figure 4.

tail by Hammer and Snow [14]. The position of the microphones in the cheeks rather than in the ears was justified by the size (1.4 inch) of the special type 4 moving coil microphones. According to Fletcher [41], the experiments with "Oscar" proved that signals with higher fidelity could be obtained by reproducing the human by way of a manikin.

Fletcher also acknowledged that the use of two microphones could create a spatial sound effect. Based on the knowledge gathered with "Oscar" he devised a system for "auditory perspective" intended to be used in cinemas, as "auditory perspective" was a topic of considerable interest in around 1900 [47].

During the winter and spring of 1931/1932 Bell Labs, in cooperation with Mr. Stokowski from the Philadelpha Symphony Orchestra, undertook a series of tests of musical reproduction using "Oscar" as a recording device, continuing a cooperation that started years ago. During these experiments the binaural signals obtained with "Oscar" were also compared with the live listening experience [14].

"Oscar" was presented to the public at the 1933 World Fair in Chicago [11] and was later displayed in the Museum of Science and Industry in Chicago [44, 43, 48] until 1951 when the manikin was replaced by another[12]. At the World Fair, and later in the museum, "Oscar" was placed on a glassed-in stage, and headphones were connected to the manikin. A speaking person then walked around "Oscar" and the person wearing the headsets could perceive that the speaking person was moving, a startling effect at this time. However, the "auditory spectators" could not only hear the moving source but also see it and in this way an important concurring cue for localization was present. Hammer and Snow [14] as well as Tinkham [44] reported that localization errors, mainly front-back-confusion (source in the front, but perceived in the back) and distance errors, were not the exception but the normal occurrence when no visual cues are present or when the source signal was not continuous. This phenomenon would be understood, partially, only about 40 years later and is still a concern in binaural technology, as will become clear through the course of this article.

Later, Fletcher dedicated his interest to the reproduction of high-fidelity sounds, not through headphones but loudspeakers. From the initial idea of using an infinite number of microphones and loudspeakers, certainly associated with modern wave-field synthesis, the researchers at Bell Labs came to the conclusion that three microphones or loudspeakers were sufficient [49, 50]. This method, and others that used only two microphones, were later (also) called stereophony [50].

In Europe, De Boer and Vermeulen, from the Dutch company Philips, presented two devices in the 1930s to obtain "binaural" signals to be reproduced by headphones as part of a "binaural hearing aid" [17]. The first device was a sphere with a diameter of 22 cm with microphones placed on the circumference. The other device was a manikin, the first and (still) the only manikin that imitated a woman. The head of the manikin, of the type commonly used in department stores, had its capacitive, and still large, microphones placed "in" the simulated pinnae, as one can see in Figure 5. In this way, for the first time the pinnae might have influenced the signals obtained. Also, for the first time De Boer and Vermeulen noted a modification of the timbre of the signals obtained in comparison to the signals heard by a human listener, but no explanation was found.

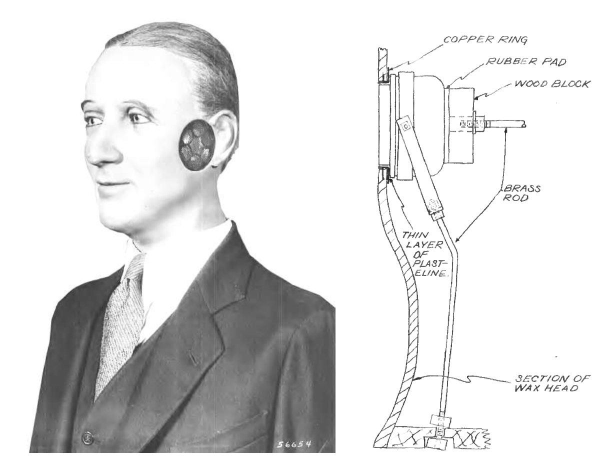

Figure 4. Oscar, the manikin made by Fletcher and colleagues at Bell Laboratories. Lateral view and detail of microphone fitting [14].


Figure 5. The female manikin of De Boer and Vermeulen, with microphones placed "inside" the simulated pinnae [17].

According to Fernberger [51] Rosenberg and Slavinsky [52] also used a manikin to investigate the directional properties of hearing at the end of the 1930s. According to Fernberger two microphones were mounted "in the head of a lifelike dummy at the position of the two eardrums". The author of the current article does not have access to the original article by Rosenberg and Slavinsky [52], but considering the size of the microphones available at this time and the knowledge on the influence of the external ear on

[11] According to the memoirs of Fletcher [33] this happened in 1932, but the World Fair opened only in 1933 and remained open until 1934.

[12] Personal communication of Mr. Ritzler, from the Museum of Science and Industry Chicago on 2nd September 2008.

the signals it is more likely that the microphones were at the position of the ears instead being at the position of the eardrums.

During World War II, only small advances regarding binaural technology were documented. The knowledge on binaural hearing was used mainly for military purposes, and different artifacts to localize aircraft, submarines and ships were constructed (e.g. [53, 54]). One of these devices, an apparatus to localize aircraft, incorporated two or four horns as receivers for sound signals to be heard by a human operator [55]. Also, for the military, Dickson and colleagues [56] developed a wooden head with a microphone placed in the position where one of the ears would be, to measure the sound transmission of flying helmets, those made of leather this time.[13]

In 1940 De Boer applied for a Dutch patent with the description of an apparatus of stereophonic sound transmission that used an "artificial head" for sound pick-up and three loudspeakers for reproduction, two for the high frequencies and one for the low frequencies. The artificial head was a simple sphere, which should have at least a diameter of 14 cm. In his patent application, which in 1947 was also filed in the USA [69], De Boer discussed the effects of different diameters on the sound signals coming to the conclusion that the "artificial head" should have at least a diameter of 14 cm. Based on this patent De Boer and his colleague Vermeulen submitted another patent in 1942 in the Netherlands and in 1948 in the USA [70] for an apparatus to adjust the stereophonic effect in any stereophonic transmission. They proposed a T-configuration of resistors to modify the apparent size of the "artificial head" reflected in binaural signals.

At that time stereophonic techniques that did not use an artificial head were improved, and were shown to be more simple and compatible with the reproduction technology of the day. Also, one of the big problems at that time was the recording of multiple signals while maintaining the phase information between them. This was resolved only in the mid 1940s when magnetic tape recorders became more widely available[14], including magnetic tape recorders for mutli-channel recording. Other problems at this time were the limited frequency response and dynamic range of recording equipment as well as microphones and headphones or loudspeakers.

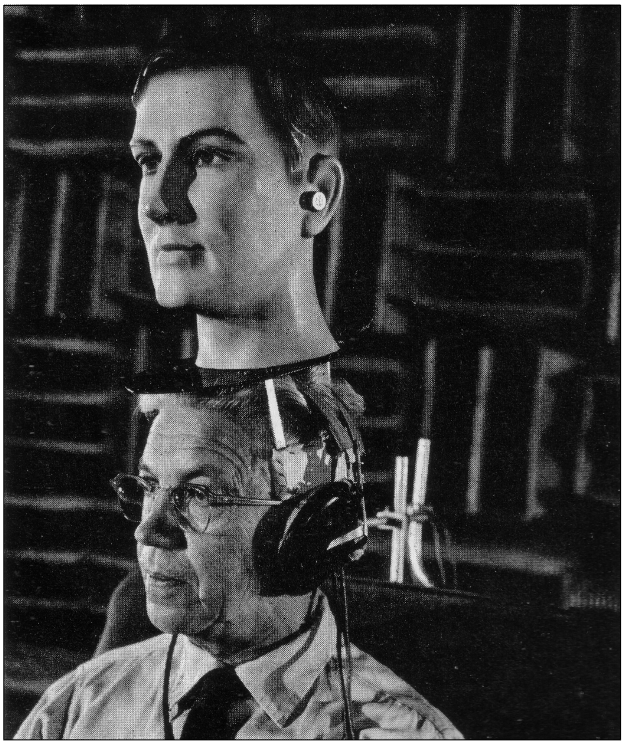

Figure 6. The artificial head "Oscar II" being used by H. Fletcher in localization experiments called "double dome" research, after [75].

After Geluk [73, 74], shortly after World War II in the Netherlands, transmission of a binaural radio program started and was maintained for some time, using very probably the manikin of De Boer and Vermeulen [27].

Based on "Oscar", Bell Labs developed "Oscar II" in the 1940s. According to Figure 6 this head did, in fact, have the microphones placed in the ears, but they were then mounted with their membranes at about 5 mm distance outside the *cavum conchae*.

4. The fifties

Push-started by the new recording technology using magnetic tapes that allowed reasonable preservation of phase differences between signals and larger dynamic range, new applications for stereophonic and binaural technology were devised, for instance, in industry [44]. As early as the beginning of the 1950s Snyder [43] concluded that a technology that could preserve all important aspects of a sound event would have a large field of applications, not only in the music and broadcasting industry. His prediction would later be confirmed, as the reader will see in the course of this article.

David C. Apps and his colleagues at General Motors USA were probably the first researchers to use stereophonic recording in the automotive industry, working during the 1950s until around 1970 [76, 77]. The title of Apps' article "*The Use of Binaural Tape Recording in Automotive*

[13] The "artificial head" of Dickson and colleagues, and also the heads used by many others to measure transmission loss of helmets or hearing protectors, are also known as acoustical test fixtures (ATF). They are often monaural devices and other very special requirements such as the transmission loss of the head itself or impedance changes due to the presence of the hearing protector are much more important than the fine structure of the HRTF. Therefore, they are mostly not artificial heads for binaural pick-up as understood in the current article and the reader interested in ATFs may consult the specific literature [57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67]. In 1982 Richter *et al.* [68] published results for plug-type hearing protectors using commercially available manikins (BK 4128 e HMS II 4.n).

[14] The first magnetic tape recording device was patented in 1898 by the Danish inventor Valdemar Poulsen [71] but magnetic tape recording was not used successfully before around 1936 in Germany (Magnetophone) and after World War II worldwide [72, 43, 44]. For more information about magnetic tape recording see, for example, the publications of M. Camras in the Proceedings of the Institute of Radio Engineers.

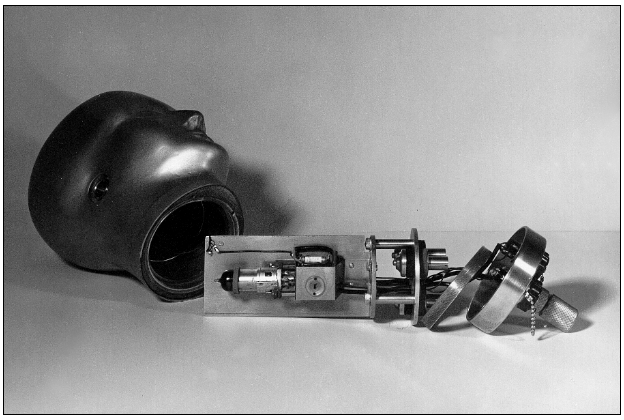

Figure 7. The artificial head made by AKG for sound localization experiments at Budapest University, Courtesy: AKG.

Noise Problems" suggested, as was common at that time and still occasionally occurs, that binaural signals were obtained. However, on reading the article one discovers that Apps and his colleagues did not use an artificial head or manikin but only spaced microphones. Shedlowsky (cited in [77]), who worked with Apps at General Motors, wrote later, in 1965, that the system was developed and used because it gives more realism to the recordings than single microphone recordings and that these recordings were required because it was already known that evaluations of car interior noise using only sound pressure level measurements and spectrograms were not sufficient. Shedlowsky also reported that previous attempts to obtain better recordings had failed, and that only the use of magnetic tape recording equipment, and later manikins, provides the type of recordings required.

For research on spatial hearing to be carried out at the Budapest University, Hungary, AKG from Austria manufactured a small number of artificial heads in 1951. The heads were made of wood and did not have pinnae as shown in Figure 7. The microphones were AKG omnidirectional condenser microphones.

Bixler claims to have build a "binaural" pick-up system, but examination of the corresponding article [78] reveals that the system is a two-microphone pick-up system with a baffle as the acoustic septum and, thus, it is far from being a binaural pick-up system, as will be further considered herein.

Also, individuals and companies related to the music and broadcasting industries worked on "binaural technologies". André Charlin, a French recording engineer, presented his *tête artificielle* in 1954. His "head", also called *tête Charlin* (Figure 8), was a balloon made of leather, very similar to those patented by Fletcher and Sivian in 1927 [15]. Later Georges Kisselhoff, a colleague of Charlin, experimented with other geometries and used them in music recordings.

In 1955, the German company Schoeps presented a microphone composed of an aluminium sphere 20 cm in diameter (Figure 9) with two omnidirectional microphones placed on the circumference. Schoeps only produced a few examples of this microphone, which was called *Kugelflächenmikrophon*.

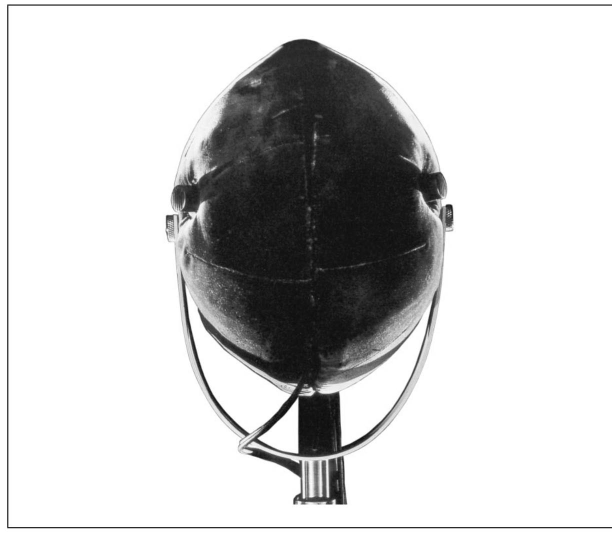

Figure 8. The *tète Charlin* [79].

Figure 9. The experimental microphone of Schoeps [80].

The approach of Fletcher and Sivian, Jones, Charlin, Kisselhoff, Schoeps and others, for instance Madsen and Jecklin, should be considered stereophony with an acoustic septum (*Trennkörperstereofonie*) and not exactly as binaural recording technology because not all the important elements for transference of the sound wave to the eardrum were considered, in particular, the torso and pinnae were excluded. At this time, no company was willing to put money into research activities to develop more true-to-original recording devices. In the following years several types of microphone set-ups with an acoustic septum in between had been invented, considering also discs and triangular geometries for the separating elements [80, 81]. However, industrial production of such devices did not start until the 1990s with Neumann's KFM100

Figure 10. Artifical heads used by Nordlund and colleagues [87, 89]. (a) Head with ear canals, (b) head without ear canals.

and Schoep's KFM6 and KFM360, principally based on Theile's work.

At the end of the 1950s, Mills [82] and Wansdronk and Meyer [83] experimented with models of the human head in order to investigate sound diffraction at the human head. These experiments were undertaken because very small hearing aids had become available and their microphones captured the sound field in a form strongly influenced by the human body. The head used by Mills was not described in detail, but had one-inch WE 640AA condenser microphones placed in each ear with the diaphragm placed flush to the entrance of the ear canal [82]. Wansdronk and Meyer only measured the "head-related transfer functions" between a sound source and the hearing aid, mounted on real heads, as well as on different devices to model the human head, and therefore no microphones were installed in the devices.[15] Nevertheless they suggested the use of a standard artificial head for measurements of hearing aids, an idea that became a reality only about 15 years later when KEMAR was introduced.

5. The sixties and seventies: New advances in binaural technology

The sixties and seventies can be considered a golden age for binaural technology. Numerous studies related to human hearing, transformation of sound signals due to the human head and other elements were published and a large number of more and more sophisticated artificial heads appeared. This line of research also resulted in the first reference manikin, KEMAR, and Vorländer described this time as the "KEMAR years" [84]. Along with their use in research on sound modification and human sound perception, artificial heads and manikins also started to be used in room acoustics, and in the development of hearing aids and other communication devices, such as headphones and microphones.

In different studies related to the interaural time and intensity differences with respect to localization and directional audiometry (e.g. [85, 86, 87]) and in research related to intelligibility [88, 89] Nordlund and colleagues used different artificial heads made by the researchers out of craniums and plastic material [85, 87] (Figure 10). The heads developed used one-inch condenser microphones, which were the standard microphones in artificial heads until the 1980s. One of the heads (Figure 10a) also had its microphones placed at the approximate position of the eardrum, featuring also simulations of ear canals. This head, described in [87], together with an ATF described by Flottorp and Quist-Hannssen [57], is likely to be the first ever to feature simulations of ear canals, which where 27 mm in length and 7 mm in diameter. Unfortunately the authors do not give detailed information about the coupling of the ear canals to the microphone capsules.

In 1966, Bauer *et al.* of the CBS laboratories [90, 91] presented a manikin (Figure 11) based on anthropometric data from seven astronauts[16]. The manikin was developed for measurements of sound transmission through astronaut helmets and testing of communication equipment, such as headphones and microphones, to be used in spaceships. For this reason, the manikin also had an artificial voice, implemented using a loudspeaker.

According to Burkhard [92] the manikin of Bauer and colleagues was also the first constructed in order to consider the acoustic impedance of real ears. For this reason pinnae and an ear canal were modelled and one-inch microphones were connected to the ear canal by an added volume and an acoustical resistance (Figure 12). The ear canal even allowed the insertion of small headphones. In principle, the sound pressure level corresponding to that at the eardrum of a real person was obtained, but by using an electrical circuit the sound pressure level at the entrance of the ear canal could be calculated, which was useful as experimental data were usually obtained at the entrance of the ear canal. Another electrical circuit was responsible for weighting the sound pressure level with the equal loudness curves of Fletcher and Munson, a procedure very useful at a time when signal processing was still difficult.

[15] They compared these transfer functions to the transfer functions measured by Wiener for transmission between a source and the entrance of the auditory canal. Simple spheres (with and without pinnae), a box with pinnae and a model of a human head were used, but the transfer functions were found to be very different to those obtained when the hearing aid was attached to a real head. They described their artificial head as a plaster model of the head of one of their cooperators. As the authors measured the transfer function between a sound source and the microphone of the hearing aid, this mounted behind the ear, there was no need to install microphones in the devices or to model an ear canal.

[16] The study of Torick, Bauer and colleagues was financed by NASA.

Figure 11. The manikin developed by Bauer, Torick and colleagues [90].

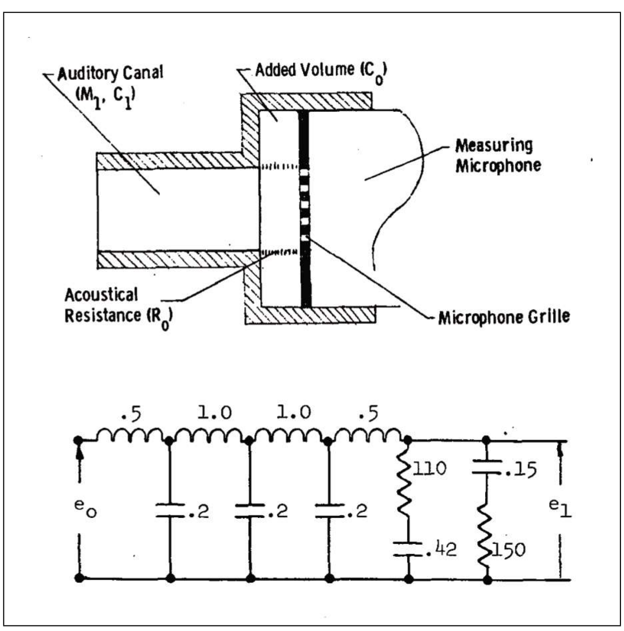

Figure 12. The ear canal simulator used in the manikin developed by Bauer, Torick and colleagues [90]. Cross-section and equivalent electrical circuit.

Also, according to Burkhard [92] Kasten and Lotterman used an artificial head in 1967 to study diffraction effects on hearing aids that blocked the ear canal entrance. For this reason they do not consider a simulation of the ear canal for their head [93].

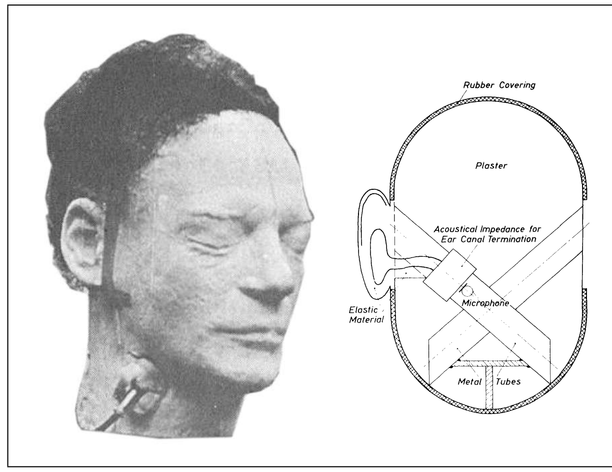

Figure 13. The artificial head developed at the Heinrich-Hertz institute [95].

Damaske and Wagner, from the third Institute of Physics at Göttingen University, Germany, reported, in 1968, localization experiments using their own manikin [94].

In 1969, Kürer, Plenge and Wilkens, of the Heinrich-Hertz Institute at Berlin's Technical University presented an artificial head that imitated even the human skull. Kürer, Plenge and Wilkens stated that they also gave special attention to the pinnae, these being copies of the pinnae of one of the authors, made of elastic material. An ear canal was simulated as well as the eardrum. The head used Neumann omnidirectional condenser microphones KM 83 21mm in diameter [95, 96, 97]. For reproduction Kürer and colleagues recommended the use of free-field equalized headphones.

In 1970, a German patent was filed for a system comprising the manikin and a set-up for reproduction with loudspeakers and signal processing [96].

Also in 1969, the German company Sennheiser presented a manikin named "Oskar" at the International Radiocommunications Fair in Berlin (Figure 14). It was made especially for the recording of radio plays, and was used later also for music recordings. The manikin was equipped with omnidirectional condenser microphones, including an imitation of an ear canal. The pinnae were made by a dentist copying the pinnae of one of his colleagues, using an elastic material.

The manikins produced until this time were usually manikins adapted from those used in department stores (Firestone, Fletcher, DeBoer & Vermeulen, AKG), or individual products, in the latter cases normally copies of the heads and often pinnae of one of the researchers (e.g. Nordlund & Lidén, Sennheiser, Kürer *et al.*). For this reason when reproducing the signals obtained modification of the timbre and localization errors, such as front-back confusion, in-head localization and up-down confusion, occurred. And another big challenge was still to be overcome, the definition and creation of a manikin that represented with sufficient fidelity an average adult and could be standardized, as suggessted by Wansdronk [83].

Figure 14. The manikin “Oskar” of Sennheiser. Courtesy Sennheiser.

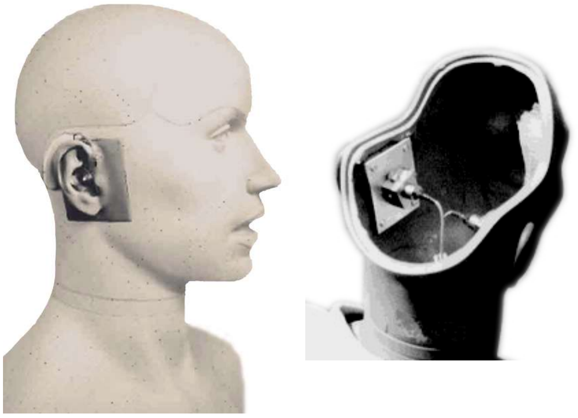

Figure 15. Kemar - the first representative manikin [98].

Figure 16. The Neumann KU80 artificial head, after www.drm-berlin.de.

Burkhard and Sachs, from Industrial Research Inc., a subsidiary of Knowles Inc., were the first to use large-scale anthropometric data to define the geometry of a manikin. The development was pushed by the need for a device that would properly account for diffraction effects of the human body in the evaluation of small hearing aids placed on the head in proximity to the ear, a problem already considered by Wansdronk [83] using an artificial head.

Following this line they presented KEMAR (Figure 15) in 1972, being principally developed for the evaluation of hearing aids under *in-situ* conditions [92, 98, 99]. All elements that influence sound propagation from the source to the eardrum were modelled based on anthropometric data from male US-Air Force personnel. KEMAR could also be equipped with an artificial ear, simulating the impedance of a human ear properly. Even the impedance of human skin was modelled as suggested earlier by Wansdronk [83].

The ear simulator, optional for one or both ears, simulated the impedance of the ear canal and eardrum for open, partially occluded or totally occluded ear canals, an important condition for the evaluation of hearing aids or other sound sources that are close to the ear. Also, to study the effect of different pinnae, KEMAR gained different sizes of pinnae over the years, the first being in 1979 [100]. With a geometry based on anthropometric data and simulation of impedances KEMAR turned out to be the first representative manikin and was also adopted as a reference for *in-situ* measurements of hearing aids according to IEC 959 - *Technical Report - Provisional head and torso simulator for acoustic measurements on air conduction hearing aids* [101]. Until today the head-related transfer functions ($HRTF$) of KEMAR [102] serve as references and can be found on the Internet. In addition to the measurement of hearing aids under *in-situ* conditions, Burkhard used KEMAR back in 1978 for the measurement of headphones and plug-type hearing protectors [103].

Based on the manikin of Kürer, Plenge and Wilkens from Berlin’s Heinrich-Hertz-Institute [95, 97], German microphone manufacturer Neumann presented their first artificial head KU80 (Figure 16) in 1973 at Berlin’s International Radiocommunications Fair[17] [104, 105]. The head used the same KM 83 microphones as the head of Kürer *et al.* and had a mechanically achieved free-field equalization.

Researchers from Oldenburg’s University, developed several variations of artificial heads in the 1970s [106, 107, 108], reporting also the idea of implementing an equalization independent of the sound incidence direction [108].

Another artificial head, especially intended for non-professional use, was launched on the market in 1973/1974 by the German branch of the Austrian AKG. The

[17] In German: *Internationale Rundfunkausstellung*.

model D99c, also called “Harry”, was geometrically extremely simplified and used dynamic microphones instead of condenser ones, which were common in the other heads.

With several artificial heads on the market, they were also used by professionals in the audio sector. Beginning with Berlin’s International Radiocommunications Fair in 1973 the heads were then used for radio-plays [109, 110]. The radio-plays recorded in this way were a success, in contrast to the Dutch attempt in the late 1940s, and later music was also recorded using the same technique.

However, some problems still occurred with the binaural recordings, these being noted particularly by radio-engineers and sound technicians. One problem was the low signal-to-noise ratio of the recording system, especially noticeable when using headphones for reproduction. Using loudspeakers the problem was minor, but the binaural signals were not readily compatible with loudspeaker reproduction, giving rise to cross-talk and also to changes in timbre as the signals are likely to be influenced twice by a head-related transfer function; firstly between the original source and the recording head and secondly between the virtual source (loudspeaker) and the head of the listener.

With headphone cross-talk was not an issue, but alteration of the timbre still needed to be prevented. One of the greatest problems in headphone reproduction was a large error in the localization of the sound event. For example, errors such as front-back confusion (sources recorded at the front were heard in the rear) gave rise to a “black hole” in front of the listener. This was heavily criticized by recording engineers as the orchestra or band musicians who were at front of the recording head were perceived by the listener to be at the rear upon reproduction. Other issues were up-down confusion and errors in distance perception, the latter giving rise also to in-head localization. All of these issues were not new; front-back-confusion had been reported in the 1930s by persons who had listened to signals recorded by Fletcher’s “Oscar”. In the 1970s recording engineers concluded that the dummy head recording technique is better suited for some types of music, orchestras and rooms than others [111, 110]. Facing such hard criticism, Wilkens claimed that the objective of the development of dummy heads was to find a way to evaluate different concert halls without the evaluator being physically present in the concert hall and that localization, especially front-back-localization, is of minor importance to this aim [110].

Even with the reported problems, very much discussed in the 1970s, recording engineers and also amateurs showed great interest in making binaural recordings. To attend the demand at a reasonable price several manufacturers from the audio branch launched and patented binaural recording equipment, such as JVC, Sennheiser and Sony. A combination of headphones and microphones to record binaurally and to reproduce the recording immediately was patented in 1970 by Usami and Kato [112] and commercialized, for example, by JVC as the HM-200E binaural headphone / microphone combination. It combined circumaural closed headphones with electret microphone capsules to obtain “binaural” signals. As one can see in Figure 18 the capsules were mounted in an approximated pinnae molded into the outer shell of the headphones.

Figure 17. The AKG D99c artificial head. Courtesy AKG.

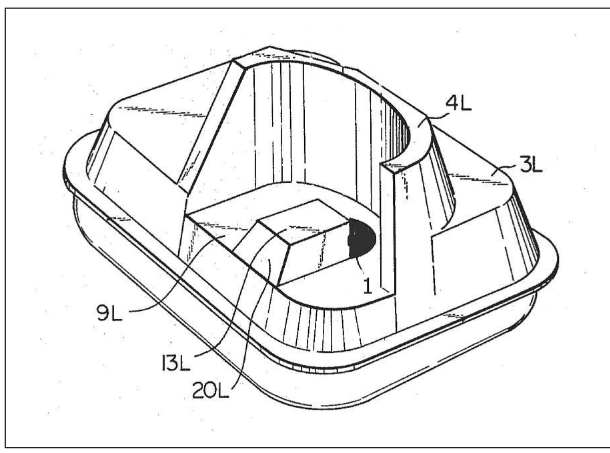

Figure 18. View of the left earphone of the binaural headset patented by Usami and Kato, showing the electret capsules (1) position in the simulated pinnae (4L, 9L, 20L) of the earphone [112].

Sennheiser launched in 1974[18] a binaural microphone headset, the MKE-2002, often referred to as the first one ever. It was similar to a stethoscope and made binaural recordings possible when used on a person’s head or on the optional plastic head, as shown in Figure 19a. The pre-polarized electret microphones were placed in the *cavum conchae* (*meatus acusticus externus*) according to Figure 19b.

A device patented by Yasuda [114], on behalf of Sony, featured two microphones with windscreens to be placed on a listener’s head, or a plastic head (Figure 20).

In addition to this equipment many persons interested in audio recording started to made their own “binaural” recording equipment, such as heads and headsets, and

[18] The patent was granted in 1976 [113].

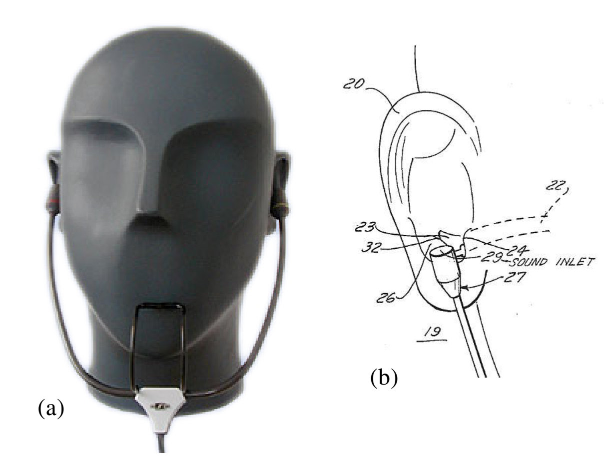

Figure 19. The MKE-2002 binaural microphone headset [113]. Courtesy Sennheiser. (a) Mouted on the plastic head, (b) detail of the positioning of the microphone.

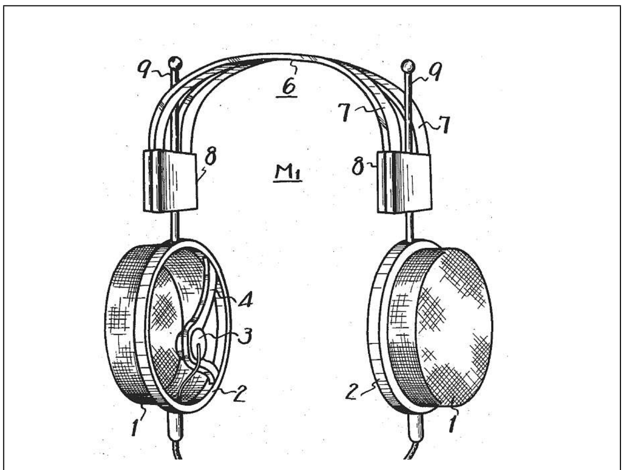

Figure 20. Binaural microphone patented by Yasuda, using two electret microphone capsules (3) and two windscreens (1) [114].

many manuals for the construction of a home-made artificial head can still be found on the Internet. In spite of the interest by audio amateurs the systems commercialized by JVC, Sennheiser or Sony were discontinued after a few years.

To circumvent the problems related to binaural technology many studies were developed in the 1970s. Laws *et al.* [115] used probe-microphones, as previously used in 1946 [116, 117], to obtain signals that corresponded as closely as possible to the signals at the eardrum of a listener. They showed, using the most precise microphones available, that not only the presence of the shoulders and torso, but also the sufficiently exact simulation of the pinnae, was important for a true-to-original sound image and to reduce errors in localization and distance perception. Therefore, two additional details, important for truly binaural signals, have been identified. Also, the need for a correct and exact equalization of the whole recording and reproduction chain becomes evident, as well as the requirement for a lower signal-to-noise-ratio. As a result of the investigations in 1977 Laws *et al.* presented the IENT77 recording head [118, 119].

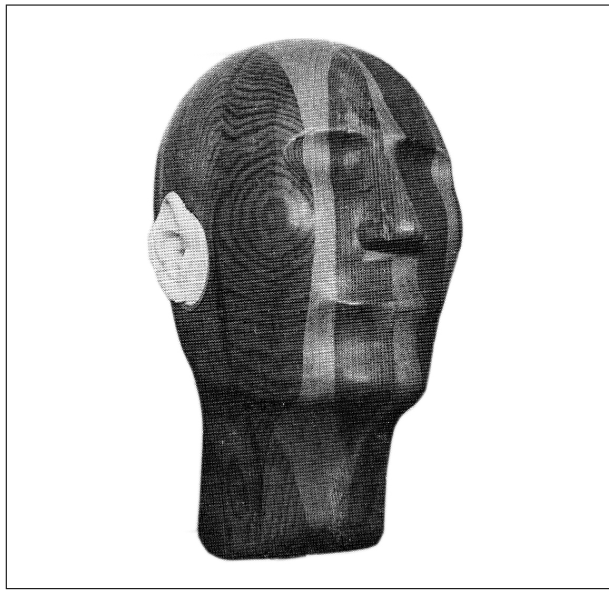

Figure 21. The wooden artificial head made by Kleiner [120].

Kleiner [120] compared commercially available systems for binaural recording (Sennheiser MKE-2002, AKG D99c and Neumann KU80) with his own wooden artificial head. The head build by Kleiner (Figure 21) featured pinnae made of soft silicone rubber, these being copies of the human pinnae, and the position of the 1/2-inch microphone in the ear canal was variable. As an output of his work Kleiner suggested that an artificial head should have the microphones placed in the plane of the concha, but acknowledged that the then available half-inch microphones still presented too much background noise for this purpose. He also built ten artificial heads out of expanded polystyrene foam with the microphones placed in the plane of the concha. These heads were used for sound pick-up in the Stockholm concert hall, which was the objective of the development of many artificial heads and manikins at that time [110].

Also, Conant [121], from the famous Bolt Beranek and Newman Inc., published an article in 1978 reporting the use of a manikin called SAM (simulated auditory manikin) together with a system of analysis to obtain the binaural impulse response of a room as well as to make recordings of a virtual orchestra, the latter reproduced by a loudspeaker in the room. Signals were then reproduced by headphones. The manikin, particularly the head and the pinnae, were copies from Conant's own head and pinnae, but according to Conant the pinnae simulation could be changed easily. The microphones were 1/2-inch condenser microphones with free-field equalization, placed in the pinnae without a simulation of the ear-canal. Conant also reported the equalization of the headphones to be used, placing them on the manikin.

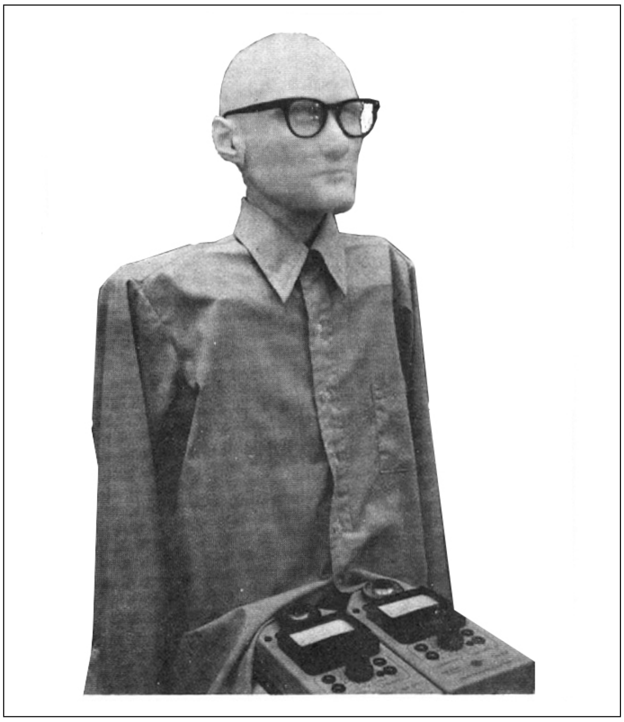

Figure 22. The manikin SAM used by Conant [121].

Figure 23. The KU81 prototype head from Bochum's Ruhr University. Courtesy: J. Blauert.

6. The eighties: Industrial applications

In the 1980s the interest in recording and measuring technical sound, such as in automobiles, binaurally was increasing. But the recording equipment at this time was not ready for such use, suffering principally from a limited dynamic range, low frequency sounds in a driving vehicle can achieve easily 120 dBlin, and a low signal-to-noise-ratio.

Furthermore, for the measurement or analysis of recorded signals at this time, it was required that the results would be comparable to the results from signals obtained with measurement microphones. This somewhat paradoxical requirement was achieved by equalization of the signal before analysis or storage, removing totally or partially the influence of the manikin or head on the signals. Naturally, for headphone reproduction, this must be replaced again.

One of the results of the studies carried out in the 1970s was the presentation of the KU81 artificial head by Neumann GmbH in 1981. The KU81, especially developed for use in the broadcasting industry [122], was based on the KU80 and prototype heads from the Institute of Radio communications in Munich and Bochum's Ruhr University (Figure 23).

After a detailed description [123, 124, 125, 126, 105] the new head passed through two stages of development. First, the one-inch microphones that were used in the KU80 were replaced by smaller prepolarized electret microphones [123], reducing in this way the roll-off in the frequency response at high frequencies, due to the coupling of the larger one-inch microphones to the ear canal. The pinnae of the KU81 were chosen according to a criterion of minimal difference of the resulting HRTF from the mean of the HRTFs of different persons. Also, the position of the pinnae was modified. In a second stage, the one-inch microphones were used again, due to the better signal-to-noise ratio. The roll-off problem at higher frequencies was then dealt with by a refined coupling of the microphone to the ear canal, using additionally a tuneable resonator [125, 126]. The coupling device was also responsible for the new diffuse-field equalization, instead of the free-field equalization used in the former KU80, seeking better compatibility with signal reproduction by loudspeakers or diffuse-field equalized headphones [122].

Between 1980 and 1982, Genuit *et al.* from Aachen University *Institut für elektrische Nachrichtentechnik* (Institute for Telecommunications), developed, in collaboration with a German car manufacturer, a binaural recording and measurement system, originally called IENT 81 and described in detail in [127, 128, 129]. The system (Figure 24) was designed principally for the measurement, recording and later reproduction of technical sounds via headphones, and was based on the manikin developed by Laws and Platte [118, 119] from the same institute. It featured a human-like geometry and pinnae, and used 1/2 inch B&K condenser microphones connected to an ear canal only 4 mm in extension[19]. It also incorporated some new features, particularly those required for calibrated measurements and reproductions [128, 129]. The system was later called AachenHead or HMS I [130] and was first patented in 1983 [128, 129]. The IENT81 and also the first HMS I had only a free-field equalization interface [27, 130], in contrast with the Neumann KU81 head, which used diffuse-field equalization, because in the HEAD-acoustics system preference was given to headphone reproduction and comparability with single microphone signals. Later, the system also gained what was called an independent-of-direction equalization, offsetting

[19] Only the first 4 mm of the ear canal, seen from the pinna, were modelled. This first part of the ear canal still accounts for direction-dependent modifications of the sound waves and must therefore be modelled physically.

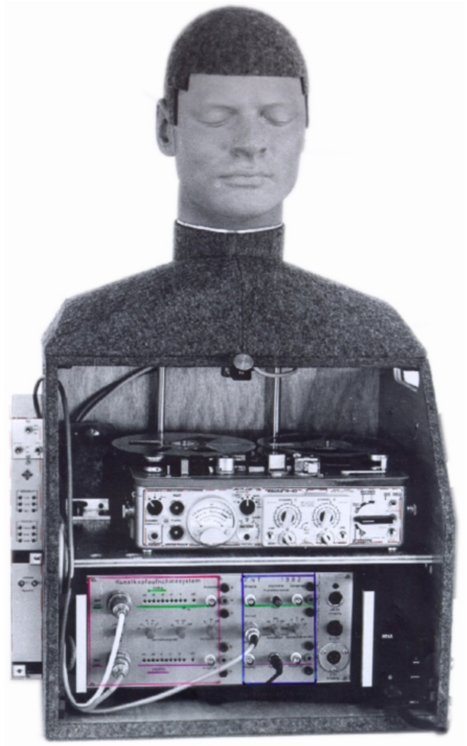

Figure 24. The IENT81, later HMS I, measurement system developed at IENT Aachen and commercialized by HEAD-acoustics. Courtesy: HEAD-acoustics.

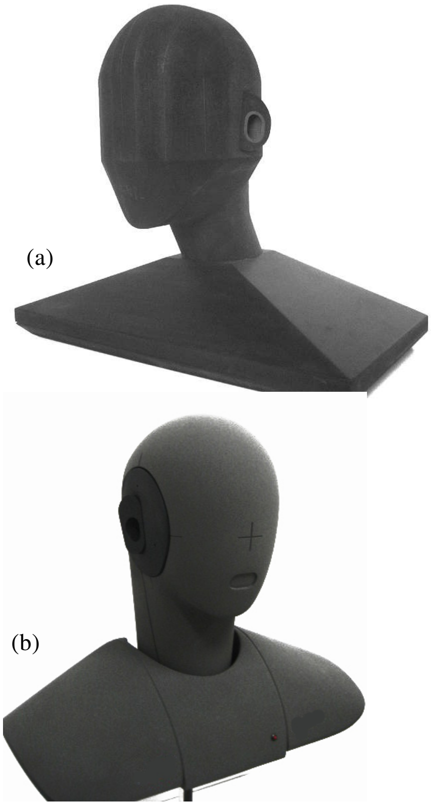

Figure 25. The manikins developed at IENT Aachen. (a) Genuit's prototype manikin, (b) HMS II.

only pinnae effects that are independent of direction. In this way, the signals are no longer directly comparable with single microphone signals.

In the mid-80s another manikin, called IENT84 or HMS II was developed. It was based on studies by Genuit [131, 132, 133] on the simplification of the sound modifying elements. In his studies Genuit simplified the geometry of the shoulders, the head and the pinnae with simple and mathematically describable geometric elements. The dimensions of a prototype of the new manikin, a head and shoulder simulator (Figure 25a), were based on anthropometric data from seven persons selected by Genuit [132, 84].

The dimensions of the HMS II, also featuring head and shoulder simulation, were then based on anthropometric data from Genuit and Essen University [27, 134], but in order to conform with standards such as IEC959 some modifications to the outer dimensions were necessary, resulting in their reduction. The approach of the simplification of the elements of the manikin was maintained in order to obtain a representative manikin that could be standardized more easily and to a greater extent than human-like manikins such as KEMAR. Also, the new manikin had a well-defined ear canal entry point. This standardization was thought to provide the possibility to compare *strictu-sensu* signals from telecommunication devices in accordance with ITU-T, even though the signals would not correspond exactly to those obtained at the eardrum of a real person.

The new manikin initially featured a shortened ear canal 4 mm in extension and provided two equalization interfaces, a free-field and an independent-of-direction equalization [135, 130].

A similar approach using simplification of geometric structures was taken for the torso and head of the manikin 4128 (Figure 26) designed by Brüel & Kjær [136].

For the B&K manikin human-like pinnae, ear simulators (IEC 711 and ANSI S3.25) and an artificial voice were available, qualifying the manikin for close-to-the-ear sound sources and communication devices. According to Minnaar *et al.* [137] the 4128 thus complies with the acoustical requirements of IEC 959 and both acoustical and geometrical requirements of ITU-T P.58. In the beginning, B&K was very cautious about the success of the manikin 4128, in the 1986 product catalogue the manikin still features as a tentative model [136], probably because B&K also offered other, more traditional, systems for the evaluation of telecommunication devices, the 3356 and 3357 [136]. The manikin came without any equalization, instead B&K provided the free-field transfer function for sound-incidence from the front, so equalization had to be provided externally, if required.

An interesting study was the development of a 1:10 scale manikin for measurement of the binaural impulse re-

Figure 26. Brüel & Kjær's first manikin 4128 [136].

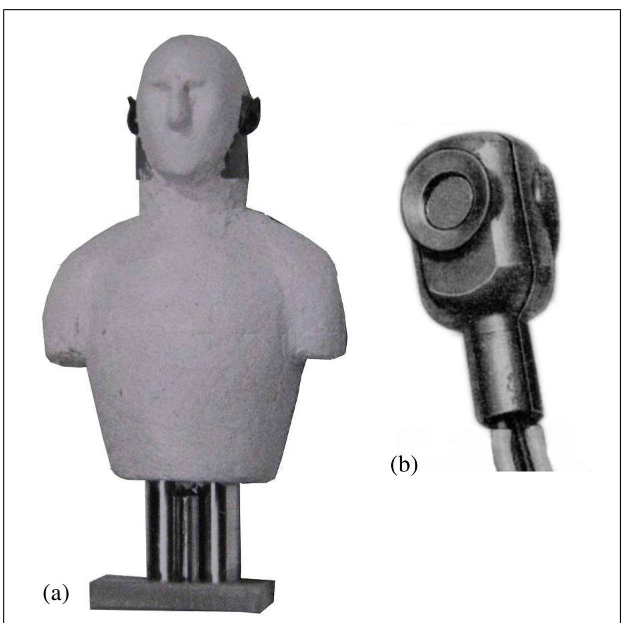

Figure 27. Scaled artifical heads or manikins. (a) Els' 1:10 scaled minikin. Courtesy: H. Els, (b) Fasold's 1:20 scaled artificial head, after [141].

sponse in scale models for room acoustics [138, 139, 140]. The big challenge was the production of the scaled pinnae, accomplished by cutting a replica of the full-scale pinna of a KU80 into slices, copying the slices in copper foil while simultaneously reducing their size, then etching the slices out of the foil, and finally reassembling them in a miniaturized pinna. The microphones used were 1/4 inch capacitive ones, coupled to an ear canal 2 mm in extension with a small cavity. A very detailed description of this work can be found in [140].

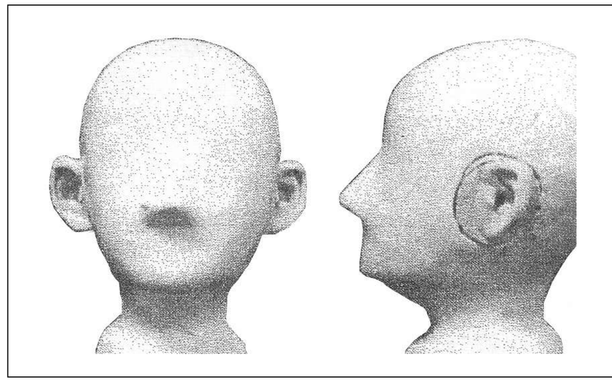

Figure 28. The artificial head made in Japan [142].

Another scaled "artificial head" was used by Fasold *et al.* (cited by Rindel [141]) in room acoustics scale models used in the reconstruction of Dresden's famous Semper opera house. The head was a 1:20 scale model, and thus extreme simplification was required. The finite size of the microphones resulted in extremely simplified "pinnae" that are large compared to the "head" as one can see in Figure 27.

For binaural recordings in automobiles Japanese researchers also made a rather simple artificial head out of a styrofoam head in around 1985 (Figure 28). According to Takao and Hashimoto [142] the styrofoam head was covered with a mixture of clay and paper and the pinnae were made of silicone, using molds of real ears. Also, an ear canal was modelled and Sony electret microphones ECM 44B were installed at the position of the tympanic membranes.

An invention called holophonics was patented in 1982 by the Argentinian Hugo Zuccarelli. The invention is very popular on the Internet, but was never published in any scientific journal and on examining the patent application [143] many doubts arise and the errors are obvious. It could be considered that the whole issue is merely a marketing exercise.

7. The nineties: Refined products and new ideas

Even with the advances made between 1960 and end of the 1980s challenges were still present.

Manufacturers that already offered manikins and artificial heads, such as Brüel & Kjær, HEAD-acoustics, Knowles and Neumann, continued to improve their products, for instance, by implementation of digital signal processing.

Brüel & Kjær introduced the 4100, which, contrary to the 4128, did not have a complete simulation of the ear canal but only a shortened ear canal 4 mm in length. Other features on the 4100 were a jacket, to simulate sound absorption of clothing, and an adjustable neck ring. Another manikin of the Danish company, the 5930 was also known as BK Pro Audio [144], and was intended for sound recording. It did not have a simulation of the ear canal and larger microphone capsules (BK 4009 studio microphones [144]) were mounted nearly flush with the ear canal entrance.

German manufacturer HEAD-acoustics started to offer versions of its manikin for sources close to the ear, such as version HMS II.4n with an ear simulator in accordance with IEC711 and human-like pinnae. Also, a version called HMS II.3 was available in 1991, featuring an ear simulator and human-like pinnae based on the ITU-T P.57 Type 3.3 artificial ear, or simplified pinnae based on the ITU-T P.57 Type 3.4 artificial ear [20], and an artificial voice.

Later, the HMS III family was introduced, differing from the HMS II due to its digital signal processing, a new third diffuse-field equalization interface and an electronic auto-calibration. In addition to the HMS family, which was a complete system with build-in signal conditioning, a HSU product line was later offered, these products not offering signal processing (AD-conversion and equalization) in the manikin.

Other companies such as the German-based Cortex Instruments[21], started to offer manikins. The MK 1, the company's first model, had a human-like head and torso geometry as shown in Figure 29, and pinnae based on IEC 959 and ITU-T P.58, but no complete ear simulator. The manikin also featured a tilting mechanisms for the head and torso that allowed for different inclinations. Equalization was carried out digitally, allowing for different curves such as free-field, diffuse-field and independent-of-direction[22]. Also, various manikins could be cascaded, and a Sennheiser HE60 electrostatic headphone was offered together with a headphone amplifier build into the manikin.

Even with the considerable number of manikins and heads available on the market research continued, especially in facilities related to acoustics.

The scaled head developed by Els [138] (Figure 27) was modified and improved by Xiang [145, 146, 147] using a slightly modified geometry for the head and torso and more precise pinnae simulations.

For hearing protector evaluation, commercially available artificial heads continued to be used [148, 68, 149], besides the heads especially developed for this purpose. Another use was the evaluation of emissions to the ear from headphones [150].

All of the signals obtained using modern heads and manikins based on anthropometric data and in accordance with IEC 959 and ITU-T P.58 still suffered alterations in timbre and false auditory impressions in some subjects. Møller *et al.* [151, 152] published an extensive study comparing KEMAR, KU80, KU81, HMS I, HMS II,

Figure 29. The MK 1 of Cortex Instruments.

B&K 4128 and the Toronto head[23], and found considerable localization problems in the median plane (front-back confusion), in-head localization and up-down confusion. Anatomical differences between the manikins or artificial heads and the listener, especially regarding the pinnae, were once again found to be responsible, especially in the case of manikins that are geometrically simplified. Since any approach using the mean of anthropometric data only is unlikely to resolve this problem, other solutions were sought. Leckschat, Schmitz and colleagues [153, 154], from the Institute of Technical Acoustics at Aachen University, developed a manikin (Figure 30) with the dimensions chosen according to a best localization performance criterion. In this approach the head-related transfer functions - HRTFs - of many people were analyzed and used in localization tests. The HRTF that provided the best localization performance for a large number of persons was then chosen and the manikin was build based on the person the chosen HRTFs pertained to. The manikin developed in this way, with its different versions of signal processing, is commercialized by the Institute of Technical Acoustics at Aachen University.

The German manufacturer Neumann took a similar approach in the development of the KU100 (Figure 31), presented at the end of the 1990s. The KU100 had a simplified head geometry and the ear canal was reduced to 4 mm length, improving also the transmission characteristics at

[20] The simplified pinnae were incorporated into ITU-T P.57 as *Type 3.4* artificial ear in 1996.

[21] Today part of 01dB, French Areva group.

[22] Cortex had to withdraw this equalization later as it was subject to a patent application of HEAD-acoustics.

[23] The Toronto head was especially developed for hearing protector measurements [58, 59].

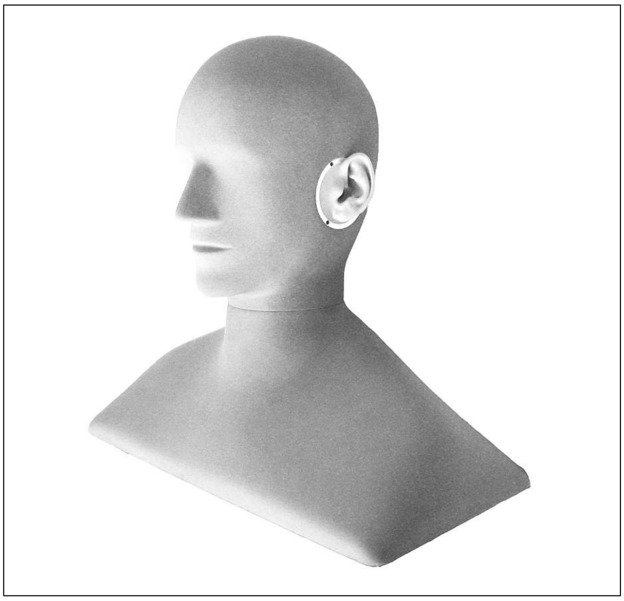

Figure 30. The best-matching manikin of Schmitz *et al.* Courtesy: ITA, Aachen.

Figure 31. The KU100 of Neumann. Courtesy: Neumann.

Figure 32. The prototype and the final Valdemar manikin from Aalborg [155].

higher frequencies. The pinnae were chosen according to a best localization performance criterion, and mirrored in order to provide symmetry. The position of the pinnae on the head also changed. Diffuse field equalization was maintained, but digital signal processing was now used, also improving the dynamic range. The microphones used in the KU100 were Neumann KK83 condenser capsules, 21 mm in diameter.

The manikin from the Aachen Institute of Technical Acoustics and the Neumann head were the first which, instead of representing an average listener and strictly following standardization, modelled a listener with high localization performance. This type of manikin or artificial head was thus called "best-matching head".

At the end of the 1990s the Acoustics group from Aalborg University, Denmark, developed a manikin called Valdemar (Figure 32) [155, 137, 156]. The manikin was developed considering HRTF measurements as well as anthropometric data. In the measurements the HRTF was split into an auriculum (pinna) transfer function (ATF) and a remaining head and torso transfer function (HTTF). The manikin's pinnae were modelled based on both the best matching and the best localization performance criteria. The whole manikin was symmetrical and the 1/2-inch microphones were positioned at the end of a short 4 mm ear canal. As one can see in Figure 32 and also on Genuit's prototype head (Figure 25a), the position of the head with respect to the torso is very natural, being more toward the front. In this way, the contribution of the shoulder reflections are more similar to those found in reality.

The Valdemar and the manikin of the Institute of Acoustics at Aachen University, which were developed based on a best-matching concept and were not in accordance with IEC 959 and ITU-T P.58, provided signals that were rated as the best obtained in localization experiments carried out by Minnaar *et al.* [137] as an extension to the work of Møller *et al.* [151, 152].

8. Current equipment and possible future developments

Apart from new products, the new millennium opens a larger discussion on the standardization or individualization of binaural recording equipment. Standardization is favored particularly in industry to allow the comparison of data obtained using different artificial heads or manikins. In contrast, individualization of recording equipment is being discussed by some researchers as a solution for prob-

Figure 33. Parametric manikin developed to represent children aged 3 to 7 years.

lems such as low localization performance in binaural recordings.

Since the start of the new millennium some manufacturers have revived the idea of offering binaural headsets. Among the products offered one can find the high-precision probe microphone solution BHM III of HEAD-acoustics that obtains the sound pressure at the entrance of the blocked ear canal. A simpler solution is B&K's 4101, which has prepolarized electret microphones to be inserted into the entrance of the ear canal, facing outward [157, 158]. Also, HEAD-acoustics and 01dB offer headphone-microphone combinations for binaural recordings. In both cases, electret capsules are installed in supraural headphones. Lokki *et al.* revived the binaural telephone system, presenting small intraural microphones, with additional microphones facing outward from the pinnae of the user [159].

Most manikins offered currently (01dB-Metravib MK2; Brüel & Kjær 4100, 4128; HEAD-acoustics HMS III/IV, HSU III, G.R.A.S. KEMAR) follow standards such as IEC 959, ANSI S.3.36-1985 and ITU-T P.58 [160]. Others (Neumann KU 100; manikin ITA Aachen, Valdemar) do not, however, they offer better localization performance when signals are heard. However, even the signals obtained with the different standardized manikins at their microphones can not be compared *strictu-sensu* due to all differences in their geometry resulting in differences in the HRTFs (see e.g. [161, 151, 162, 152, 137, 163]), even though they comply with the tolerances established in the standards for frequency response (e.g. [101, 164]).

There are also manikins and heads specifically designed for measurements, featuring an ear simulator, and those principally made for recordings, without an ear simulator. The lack of the possibility to compare the data obtained with different equipment presents a considerable problem. Since the mid-1990s a working group (DIN A2 AK8) at the German Institute for Standardization have carried out extensive comparisons of different manikins [162, 165] and based on their work the idea of a standardized shell for manikins was born [166]. The standardized shell was proposed because the differences could not be handled electronically as they are dependent on the direction of the sound incidence. According to Fastl [166] the idea received a good reception among manufactures and users and an international working group was proposed.

Considering the differences between the human form and the manikins which comply with the current standards, it became evident that other manikins are required to evaluate, for instance, hearing aids for children or for the evaluation of class-room acoustics [167]. Fels, from the Institute of Acoustics at Aachen University, investigated the changes in HRTFs and the impedance of the hearing systems of growing children [168, 169, 170]. From the anthropometric data of children of different ages numerical models and real models of artificial heads for children aged six months and between 3 and 7 years were obtained, and the HRTFs were compared to those of Genuit's manikin (Figure 25a). It was clearly evident that the HRTFs of children and adults are very different, highlighting the need to develop artificial heads especially for applications that have children as listeners.

Furthermore, with the anthropometric data collected by Burandt *et al.* [134] it becomes evident that anthropometric dimensions of persons in the 1980s in Europe were different from the 1960s data used for the development of KEMAR and adopted in the IEC 959, ANSI S.3.36-1985 and ITU-T P.58 standards. This difference is also partially reflected in the fact that best-matching heads and manikins have geometrical dimensions which are not in accordance with these standards. In this context Genuit also presented a compilation of anthropometric data from different sources [164].

Considering these discrepancies and the need for different adult and child heads a review of the standards and a new generation of artificial heads have been proposed [166, 171].

Since 2007, the development of an international project to provide a new standard for a family of artificial heads, possibly a child and an adult head, [171] has been under discussion. Such a family might be an adequate compromise between standardization and individualization of binaural recording equipment. A working group (EAA TC-PPA WG1[24]) is active under the guidance of Prof. M Vorländer and Dr. J. Fels. In this context anthropometric studies and the use of standardized and simplified outer shells have been proposed [172, 164]. At the same time another working group (IEC TC29 Electroacoustics WG21 Ear and Head Simulators) is studying an update of the IEC60959 [101].

[24] The forum of this working group can be found at http://www.eaa-fenestra.org/technical-committees/ppa/workgroups/wg1

9. Summary

In this paper, the development of binaural recording technology within the last 100 years has been described and discussed. The precise time of the appearance of the first manikin or artificial head can not be defined exactly, due to the lack of original sources and due to the question of what exactly can be considered an artificial head or manikin. The period of 1880 up to 1930 can be considered the initial phase of development of binaural recording devices, with the inventions of Goehner, Jones, Firestone, and Fletcher. The manikin of DeBoer and Vermeulen marks a transition to a second phase, and the years 1960 to 1970 can be considered an extremely fruitful phase with accelerated development of the technology, important advances related to concepts like HRTF and significant new knowledge gained regarding the function of the pinnae. Since the 1980s binaural technology has been maturing and very probably we will see new developments and even advances in standardization in the near future.

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