Auditory Sound Transmission

An Autobiographical Perspective

Jozef J. Zwislocki

Lawrence Erlbaum Associates

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To know and understand

Dedicated to the memory of my grandfather,
Ignacy Moscicki

Contents

Preface

This book is intended as a culmination of my life's research on sound transmission in the human ear. I have labored on the subject, on and off, since 1945 and touched upon many of its facets. Information gained as a result lies scattered in many articles belonging to many journals and does not lend itself to a convenient synthesis. Much of this information is bound to become lost unless it is made part of a global picture. I now feel ready to paint such a picture.

It is not my intention to present a passive review of my past work, however. Original insights have been modified according to the current state of our knowledge, and some results that remained unpublished because of time constraints and others so new that they did not yet find their way to referred journals have been included. The latter are parts of a revolution in our concepts of cochlear mechanics, which started in the late 1960s and is not yet entirely finished. The picture that is emerging is much more complicated than the classical picture whose simplicity we have to reluctantly abandon. I attempted to present some of its parts at several meetings and in related articles, but always felt that I was unable to do them justice without being able to present the picture as a whole. Consequently, I deferred full disclosure of several findings until this book.

The field of auditory science is predominantly experimental, and mathematical theory is often ignored or at least distrusted. In part, this is justified because the history of auditory research is full of examples of unrealistic mathematical and conceptual models that ignore existing experimental evidence and contradict fundamental physical laws. Nevertheless, advanced science cannot exist without mathematics. Mathematics is the universal language of quantitative science and serves as a universal glue for binding pieces of experimental evidence together. This is how I have used it in this book.

I have chosen this moment in time for writing the book for several reasons. The least scientific is my age that suggests to me that I should begin wrapping up my affairs and take a last look at the fascinating world around me. Perhaps the most scientific is the state of the science concerning auditory sound transmission. A coherent picture of the process seems finally to have emerged, and I anticipate that its main features will change little in the coming years. Of course, much cleanup work remains to be done. Past research has shown that knowledge of the sound transmission process, including the mechanical sound analysis in the cochlea of the inner ear, is essential for our understanding of the functioning of the auditory system as a whole. Because sound transmission precedes further auditory sound processing, its sufficient description is required as a basis for research on the remaining, neural part of the system, which is now coming into full swing.

Modern research on auditory sound transmission can be divided into two time periods that coincide roughly with the first and second halves of the 20th century. In the first period, experiments on postmortem preparations and associated theory were its mainstay; in the second, the weight of research shifted to live animals. Both periods brought great surprises to the interested scientific and clinical communities. During the first, G. V. Békésy discovered that sound produced traveling waves in the cochlea, partially contradicting H. Helmholtz's 19th century resonance theory. Nevertheless, he confirmed Helmholtz's prediction of a vibration maximum whose location along the cochlear canal depended on sound frequency and which was regarded by Helmholtz as a place code for pitch. During the second period, B. Johnstone and his associates and W. Rhode showed that the cochlear vibration maximum was much sharper in live animals than postmortem. D. Kemp provided the likely explanation for the difference by concluding from his experiments on sound emissions from the cochlea back to the ear canal that the cochlea supplies metabolic energy to the traveling waves. W. Brownell found experimental evidence for a likely mechanism underlying the energy supply.

Good fortune allowed my own scientific work to be a part of both periods and gave me the opportunity to interact directly with their main players at the cutting edge of research. Because of this circumstance this book has been written to some extent in a historical perspective, and this preface contains biographical notes referring to interactions with other scientists, which in part, shaped my work. They are included in response to urgings by numerous colleagues who caught glimpses of them. To make them meaningful, I first have to mention how I happened to work on sound transmission in the ear.

While studying electrical engineering at the Federal Institute of Technology in Zürich, Switzerland, I discovered that I was much more interested in human behavior and its underlying mechanisms than in engineering that dealt with inert matter. Against the advice of my mentors at the Federal Institute, who promised me a bright future in engineering, I followed my inner calling and took the first opportunity that presented itself for working on the human organism, once I concluded my engineering studies. The opportunity presented itself quite accidentally in the form of a position of a research assistant at the Department of Otolaryngology of the Medical School of Basel. My supervisor, Professor Erhadt Lüscher, who was the chairman of the department and was genuinely interested in scientific research, needed the skills of an applied physicist to complement his surgical, anatomical, and physiological ones. My task consisted of developing audiological diagnostic methods and of building the required electroacoustic equipment. One of the methods even took hold in the clinical world as the Lüscher-Zwislocki Test for monaural detection of loudness recruitment. It is still used in a modified form of the SISI test. The audiological work introduced me to auditory psychophysics and made me learn some English. I still remember plowing through such classics of the auditory literature as *Hearing* of Stevens and Davis (1938), and *Speech and Hearing* of Harvey Fletcher (1929).

Before I had left the Federal Institute, I was encouraged by my advisor, Professor Franz Tank, who happened to be the rector of the institute at that time, to undertake doctoral studies. The rules of the institute allowed me to work on my dissertation in Basel but my audiological work did not appear appropriate for the purpose. Fortunately, related study of the classical literature on hearing brought me to Helmholtz and to the controversy surrounding his resonance theory of pitch perception. To my astonishment, I discovered that the theory, as originally proposed, did not rest upon a solid foundation of physics and that the same was true for many of the arguments against it. Resolution of the situation on the basis of accepted applied physics appeared as a worthy topic for a doctoral dissertation to be submitted to the Federal Institute. My institute advisors agreed with me, so did Professor Lüscher.

The ensuing search of the literature revealed to me two authors who subsequently had a lasting effect on my career—Georg von Békésy and

Otto F. Ranke. Békésy had already performed some of his pioneering experiments on postmortem preparations of human cochleas and had been able to see that, at low frequencies, sound elicited traveling waves in their apical-most parts. He also had undertaken several series of mechanical model experiments in which he had attempted to match what then appeared as the relevant cochlear parameters. In agreement with Helmholtz's prediction, the models had revealed a vibration maximum whose location changed with sound frequency. The model cochlear partition vibrated nearly in one phase up to the vibration maximum. At the maximum, the phase changed by 180° and gave rise to a traveling wave. The vibration pattern seemed to be consistent with Helmholtz's resonance theory up to the maximum but not beyond it, and Békésy thought that he might have discovered a new physical phenomenon.

Ranke proposed two mathematical models that more or less directly attempted to explain the vibration pattern Békésy had seen. He stressed the importance of hydrodynamics in theoretical treatment of cochlear sound propagation. I had a reasonable knowledge of theoretical hydrodynamics from my engineering studies—I even had to design a water turbine; but this knowledge did not include surface waves, the kind one sees on the surface of water and in the cochlea. Fortunately, I discovered the classical work of H. Lamb on the subject, which became my hydrodynamical bible. His analysis suggested to me, somewhat to my surprise, that, formally, sound propagation in the fluid-filled cochlea could be treated mathematically like gravity waves that arise on the surface of oceans. It also convinced me that Ranke's derivations were severely flawed and led me to criticize them in my doctoral dissertation. Although Ranke was able to calculate a wave pattern resembling superficially the wave pattern later observed by Békésy and reproduced by him in one of his chapters, the similarity did not hold up under closer scrutiny. The pattern included a standing wave and a strange wave reflection depending on the depth of cochlear canals, contrary to Békésy's observations.

Combining my newly acquired knowledge of the theory of surface waves with Békésy's measurements of the compliance of the cochlear partition, I was able to derive a differential equation for sound transmission in the cochlea. The structure of the equation was formally the same as of the well-known transmission-line equation. However, it had a variable propagation coefficient because of the compliance of the cochlear partition, which increases toward the cochlear apex. As a consequence, the general solution available for the linear transmission-line equation was not applicable, and I was forced to use approximate solutions. My equation in its first form, together with its derivation and its partial solution, were first published in 1946 in a Swiss journal, Experientia. The solution showed a transversal wave on the cochlear partition, whose wavelength became shorter toward the cochlear apex and whose amplitude increased. I assumed that, in reality, the wave amplitude did not increase indefinitely but, as a result of energy losses due to friction, reached a maximum and decayed beyond it. To verify the theoretical result, I made a mechanical model of the cochlea, similar to those of Békésy's but larger and equipped with an optical system allowing the surface waves to be observed conveniently on a projection screen. The mechanical model agreed with my mathematical theory, showing a traveling wave whose amplitude increased up to a maximum and decayed beyond it. There was no uniphasic motion of the partition up to the maximum, contrary to Békésy's interpretation of his model experiments. The location of the maximum changed with sound frequency in the direction predicted by Helmholtz. I believe that this was the first demonstration of the possibility of a cochlear amplitude maximum not based on Helmholtz-type resonance but occurring in the presence of traveling waves. A year later Békésy published his amplitude and phase measurements in postmortem preparations of human cochleas. To my elation, Békésy's graphs indicated to me that they were consistent with my theoretical conclusions. The relevant 1947 article can be found in Békésy's *Experiments in Hearing* (1960) out of chronological order, ahead of some earlier articles containing descriptions of his measurements of static cochlear parameters, which I used in my numerical calculations.

My doctoral dissertation appeared in 1948 as a Supplement of Acta Oto-Laryngologica, in agreement with the rules of the Federal Technical Institute. The dissertation contains a full mathematical treatment of cochlear waves, including a complete solution of my cochlear differential equation and a theoretical analysis showing that the amplitude maximum of the waves cannot occur at the resonance location of the cochlear partition, contrary to Helmholtz's expectation. The dissertation contains numerous references to Békésy's work and reflects my admiration for it. However, it disagrees with two of its minor results. Since subsequent research proved me right, I sometimes used these disagreements to show to my students that experimental results are not always right, and theories are not always wrong. Thinking that, on the whole, my dissertation would please Békésy, I sent him a copy. His thank-you note, which arrived several months later, was congratulatory but disappointingly noncommittal.

The enormous effect the publication of my dissertation would subsequently have on my life was entirely unforeseen by me. First of all, the Technical Institute in Zürich received a letter from Ranke in which he accused me of plagiarism. The institute forwarded the letter to me with a request for an answer. I must confess, I wrote it with some relish because the accusation appeared to be entirely unjustified and only gave me an additional opportunity to criticize Ranke's theories preceding my own work. My approach was entirely different from Ranke's since it was based on a long-wave approximation and a transmission line differential equation, whereas he approached cochlear sound propagation as a boundary-value problem in which the mechanical properties of the cochlear partition were excluded from the differential equations describing fluid motion. Ranke emphasized short waves by comparison to the depth of the cochlear canals. Because of this emphasis and my long-wave approximation, the controversy between Ranke and myself was later called the short-wave–long-wave controversy. As is so often true in science, neither side was entirely correct or entirely incorrect. It is now clear from numerous experiments that the cochlear waves are relatively long before they approach their amplitude maximum but are not so in the vicinity of that maximum. For this reason, I subsequently modified my equation to include waves of any length. The modification affects somewhat the calculated wavelength and amplitude but not the fundamental insights obtained with the long-wave approximation. The latter is still used by many authors as an admissible simplification. I should add here that my criticism of Ranke's theories was not directed at the length of the waves but, rather, at the inadequacy of his mathematical derivations.

On April 21, 1950, I received a somewhat enigmatic telegram from the United States of America, which started a new phase of my life. The telegram stated: "Mass Institute Technology holding Speech Communication Conference May 31 through June third eager have you come at our expense and speak to us about your work on cochlea we can arrange boat transportation and stay here please cable letter follows + = Lock Chairman+" Having made certain with the help of some friends that the telegram actually meant what it seemed to, I telegraphed Lüscher, who was away, requesting his permission to go. He answered in French the next day: "Felicitations d'accord+" A few days after telegraphing my acceptance to Chairman Lock, I received an extensive letter from him describing the details of the trip arrangements, instructing me that I would be expected to make a presentation of 30 to 40 minutes , and apologizing for the lateness of the invitation—it was due to a delay in the approval of the necessary funds. The signature of the letter finally let me know that Lock was William N. Lock, Head of the Department of Modern Languages at M.I.T. Enclosed with the letter was a preliminary program of the conference. Of particular interest to me was the morning session of the third day, entitled: "Perception of Speech." The first paper was to be given by Georg von Békésy, then at Harvard University, the second by me, and the third by Norman R. French of Bell Telephone Laboratories. The program committee of the conference consisted of J. B. Wiesner, J. C. R. Licklider, and L. L. Beranek, in addition to the Chairman, W. N. Lock. The conference was sponsored by the Acoustical Society of America, the Carnegie Project for Scientific Aids to Learning at the Massachusetts Institute of Technology and the Psycho-Acoustic Laboratory of Harvard University.

While my travel arrangements were being finalized, Professor Lock sent me a more advanced program. Going through it, I discovered to my great surprise that Békésy's name was eliminated and replaced by that of Ranke. I was shattered. Instead of being on the same program with the famous scientist I admired, I would have to follow in the program my enemy. It was hardly possible to find a rational explanation for the change despite endless speculations. Of course, I did not change my travel plans.

I wrote my paper in German, and my English teacher translated it. Because he was British rather than American, the paper ended up by being in English rather than American English. I did not know the difference then. My English was very rudimentary—sufficient for reading my paper, which I learned almost by heart, but not sufficient for the anticipated discussion. The organizing committee kindly provided me with an interpreter for this purpose.

Because of time constraints I had to fly to the United States instead of taking a boat. I landed in New York, where I had an uncle, and took a train to Boston. Two members of the organizing committee, Lickleider and Beranek, picked me up at the railroad station and drove me to a graduate M.I.T. dormitory that was to be my residence for the duration of the Conference. A few hours later, they brought me to the residence of Professor Lock, where I and one other conference participant from Europe were invited to have dinner with the committee members and their spouses. After dinner, during which I attempted valiantly to participate in an English conversation, I found myself surrounded by all the committee members, except Lock, in what appeared to be a small living room. Sitting in comfortable chairs, they started first discretely, then less so, to ask me questions about my theory of cochlear waves. It soon became obvious that they were worried about my paper, not being certain that my theory rested on a solid scientific foundation. I suspect that the doubt arose from Ranke's paper in which he criticized my theory severely, as I was to learn subsequently. Jerry Wiesner and Leo Beranek, who knew well the kind of mathematics I was using, seemed to play the role of chief inquisitors. Somehow, using multilingual communication, I was able to dispel their concerns, and the situation ended up by turning against Ranke. In the process, I learned that the committee was unable to defray Ranke's travel expenses, and that Ranke decided not to come, sending his manuscript instead. Licklider was assigned the task of reading it. At the end of our conversation, he was not sure if he wanted to go through with it but, of course, had little choice left since the conference was to start in one day.

Trying to be fair to me, Licklider gave me a copy of Ranke's paper for study and for preparing a defense against his criticisms. I spent part of the next day doing just that with the help of an interpreter assigned to me, who was most helpful, and I regret very much not remembering his name. During the late morning, I was brought to Harvard to meet Békésy. We met in the conference room of the Psycho-Acoustic Laboratory. Békésy entered soon after we had arrived. He was a small man in a gray lab coat, rather bold, with a large nose separated from a small mouth by a small, graying mustache. He was slightly hunched over and looking down rather than up. He greeted me amiably in German and inquired about my trip and Switzerland, where he used to live in his youth. He made some courteous remarks concerning my doctoral dissertation and asked me some innocuous questions. He was evasive about the conference but thought that Ranke's theoretical work fitted it better than his experimental one. The very pleasant encounter with Békésy made his withdrawal from the conference less painful for me.

There seemed to be an evening party every day of the conference, and I gained the impression that alcohol improved considerably my command of English. In any event, it brought some interesting revelations my way. The most important provided me with an explanation of Békésy's withdrawal from the conference. Apparently, he was irked by the decision of the conference committee to invite me rather than Ranke who seems to have been a friend of his for many years. Perhaps he was also unhappy with my rather strong criticisms of Ranke's theories and my criticisms of two of his own experiments, although they were very mild. In any event, he wanted Ranke to be invited and made space for him on the program by withdrawing from it. I think that his withdrawal meant a great loss for the conference.

According to all indications, my paper was an unmitigated success, aided perhaps by my youth—I was only 28 years old and looked younger. Békésy, who came to hear it, invited me for lunch, and I received two prestigious job offers the next day—one from Harvey Fletcher of the Bell Telephone Laboratories and one from S. S. Stevens, the director of the famous Psychoacoustic Laboratory at Harvard. I admired both men enormously and regarded them as the fathers of American auditory psychophysics. I will never forget Fletcher's telephone call at 8 a.m. telling me that he had a research job for me, if I were interested, but that he suspected Stevens would make me an even better offer. He did in the evening of the same day, and I became a Research Fellow at the Psychoacoustic Laboratory. On my request, motivated by my Swiss obligations, the contract was for 1 year only but, then, became extended to 3 and eventually 6 years.

My stay at the Harvard's Psychoacoustic Laboratory was probably the most exciting period of my professional life. Békésy was the Senior Research Fellow there, and he came to my office almost every day in the afternoon for a chat in German. We spoke about everything, except science. Our scientific interactions were only sporadic but highly meaningful. They occurred mainly when Békésy felt attacked by what he called in his Experiments in Hearing "his three best enemies." I think it is a permissible indiscretion at this point in time to reveal two of them whose names are well known in auditory science—Hallowel Davis and Glen Wever. I do not know who the third one was. The attacks I remember resulted from misunderstanding the physics of the cochlea, and I felt compelled to come to Békésy's support by means of short articles in which I attempted to explain with the help of mathematics and applied physics the actual situation. Invariably, I found Békésy to be right and the "enemies" wrong. I do not mean this facetiously. On one occasion concerning sound transmission to the inner ear through bone conduction, Békésy and I disagreed. This led to an exchange of letters to the editor in which I had to apologize for misinterpreting Békésy's conclusions, and Békésy reformulated his conclusions. Stevens was the arbitrator. From the perspective of time, it appears to me that I was scientifically correct but procedurally wrong—Békésy was a senior scientist. The relationship between us was smoothed out soon after the incident, and I was welcome whenever I ventured into his office to admire his new art acquisitions. Art collection was his avocation.

The Psychoacoustic Laboratory was part of the Department of Experimental Psychology, and the Research Fellows of the laboratory were invited to participate in the Faculty meetings of the department. We also had informal daily lunches together, sitting around a large oval table. Some fascinating scientific and philosophical discussions took place around that table. The department was at its peak, having as its members such luminaries as E. G. Boring, S. S. Stevens, and B. F. Skinner. Some of the most unforgettable arguments took place between Stevens and Skinner on the subject of nature versus nurture. In those days, Skinner's behavioristic point of view was much more popular than Stevens's genetic one. The balance has been steadily changing ever since, however. Békésy rarely participated in the discussions but, sometimes, I seemed to detect a faint contemptuous smile in his expression. Perhaps some of them did not fit rationally in his world of physics. Most of the time, I shared Békésy's silence, soaking up new information coming to me from fields with which I was not familiar.

Undoubtedly, Stevens, with whom I interacted the most outside of Békésy, had the strongest influence on me, and I learned from him a lot about the scientific method, theory of measurement, psychophysics, and the structure of science and its organization. But these matters are for the most part outside the subject matter of this book, and I intend to discuss them elsewhere. Stevens did not guide my work , however. I was my own man, perhaps somewhat to his disappointment. Soon after I had arrived, he appeared in my office and, after exchanging some pleasantries, inquired about my plans. I had some very definite scientific plans and told him that I best worked by myself. He said that this was fine, but I detected a tinge of disappointment in his response. Only later did I realize that he might have hoped for me to work with him on some of his projects. Nevertheless, that is how things remained, and I was free to pursue my research within the means of the laboratory in which ever direction I wished to go. Stevens never put any pressure on me to become involved in his work, although we discussed it from time to time. Some of the projects I decided to pursue dealt with the theory of cochlear waves and some with outer ear acoustics, especially in its application to earphones and ear protectors against noise. Because work at the Psychoacoustic Laboratory was funded by the Office of Naval Research, some applied research was welcome.

Near the end of my career at Harvard, I tackled the middle ear through acoustic impedance measurements at the tympanic membrane. By performing these measurements on both healthy and pathological middle ears, I was able to analyze the middle ear function and determine the contributions of its various anatomical parts. This provided a scientific foundation for clinical diagnostic methods that are now in general use. To do the measurements, I had to invent new instruments and methods. One acoustic principle developed then has been adapted for routine clinical measurements. The work was greatly facilitated by the Eye and Ear Infirmary of the Harvard Medical School, letting me perform some of it within its facilities and supplying me with patients. I am grateful to Alan S. Feldman, who worked there at that time, for opening for me the door to the Infirmary and for helping me with the audiological evaluation of the patients.

The work on the middle ear continued when I moved to Syracuse University to organize a research laboratory within the Gordon D. Hoople Hearing and Speech Center. The laboratory was called Bioacoustic Laboratory. In part because of my ONR connection at Harvard, I was able to secure ONR funds, and the work at the laboratory took off at high speed. Soon, I had several coworkers and visiting faculty from several countries. Eberhard Zwicker from Germany, one of the most prominent members of the community of auditory scientists was one of them. I first met him at Harvard, and his stay in Syracuse coined a lasting friendship between us and our families. Our research work moved in parallel but rarely overlapping channels, however, and the literature reveals few references to each other's results. We also had different approaches. His was closer to that of an engineer, mine was strongly influenced by the medicophysiological environment at the Medical School of Basel and the psychological world at the Psychoacoustic Laboratory.

The success of the Bioacoustic Laboratory allowed it to expand beyond auditory psychophysics and the physics of the ear. Soon, we added research on the senses of touch and vision and became highly interdisciplinary, when we included physiology and anatomy. As it expanded, the laboratory changed its name twice to better reflect its activity. It first became the Laboratory of Sensory Communication, then the Institute for Sensory Research. The disciplinary diversification allowed me to include the added disciplines in my own research that now ranged beyond auditory psychophysics and applied physics and mathematics to neurophysiological experiments. Outside of psychophysics, it initially covered the sound transmitting parts of the ear, including the outer, middle and inner parts of the ear but, finally, expanded to electrophysiological recording of the responses of the cochlear sensory cells, the hair cells. The present book is the culmination of this work.

At the end of this preface I wish to gratefully acknowledge a number of people who made decisive direct or indirect contributions to my work. Unfortunately, some of them are no longer alive.

First of all, I should mention my grandfather, Ignacy Moscicki, who was a prominent physical chemist at the end of the 19th and the beginning of the 20th centuries. He instilled in me the interest in science and the moral principles according to which I attempted to live. Next, I should mention Professor Franz Tank, Rector of the Federal Technical Institute, who supervised my thesis required by the institute for an engineering diploma and guided me all the way through my doctoral work, although he was not my official advisor, my doctoral dissertation having been outside his field of specialization. Professor Erhard Luescher, for whom I worked at the University of Basel as a research assistant, introduced me to the world of biology and medicine, especially to the auditory system and diagnostic hearing testing. He taught me how to write scientific articles and insisted that sentences do not have to be long even in German. He himself was known to be an excellent writer in both German and English. Luesher was an exemplary supervisor, asking sharp questions and providing useful criticism without unnecessarily constraining the scope of my research. Professor S. Stevens launched me on the almost boundless waters of American and international science. He provided the means for me to work on as many projects as my imagination, energy, and time allowed, provided valuable philosophical and scientific guidance, and made sure I understood the importance of good writing. His future wife, Geraldine Stone, then administrative secretary, was my first and very patient editor of my English articles. Because my English was very poor at first, I saw more red ink on

my manuscript pages than ever before or afterward. She also was very helpful to me in bridging the social gap between Europe and America. Ski trips with her and Smitty Stevens (S. S. Stevens) provided badly needed relaxation. A special place must be reserved in my heart for my former wife, Sunny Zwislocki Goldman, whom I met soon after my arrival in Cambridge, Massachusetts. She introduced me to America and made it my country of choice. She was my main English teacher and a reviewer of many of my articles. She shared my life for 40 years before she died on July 17, 1992, 1 week after our wedding anniversary. She made my private life exciting without letting it interfere with my work.

In Syracuse, Gordon D. Hoople, a prominent otologist and Chairman of the Board of Trustees of Syracuse University, supported me in many ways, most importantly, by introducing me to the world of otology, locally and nationally, and by bringing me to the attention of Chancellor Tolley. He was an important reason for me to come to Syracuse. Louis DiCarlo, a well known audiologist, brought me and Syracuse University together and did most of the necessary leg work. He supported me at every possible opportunity ever since. Chancellor Tolley gave me and my associates our first independent building, where the Laboratory of Sensory Communication took shape and later developed to the Institute for Sensory Research. Wilbur LePage, as Chairman of the Department of Electrical Engineering, invited me to join his department on a dual appointment, which became the main appointment, and supported the development of our laboratory with great effectiveness. At a crucial time, Ralph Galbraith, Dean of the college allowed us to become an Institute at the departmental level and gave us effective administrative support. Vice Chancellor John Prucha allowed the institute to double its size and to become one of the best housed institutions of its kind in the Country by assigning to it a substantial portion of a first rate research building. Chancellor Melvin Eggers doubled the size of the institute again by constructing for it an additional wing of first-rate laboratory space.

The Syracuse people I mentioned above were my administrative superiors. But I must also thank my numerous coworkers without whom the success of my work would have been substantially diminished. I have to single out three individuals who made a particular difference in my scientific career. Ronald T. Verrillo and Robert B. Barlow should be considered as the two pioneers who helped me in creating the Institute for Sensory Research. Ron organized and made famous the tactile branch of the institute, Bob added vision research and connected it to the activities of the Marine Biological Laboratories at Woodshole, Massachusetts. His work has become a successor to H. K. Hartline's (Nobel, 1967) invertebrate vision research at The Rockefeller University. A very special thanks go to Earl Kletsky who was my Assistant Director during the formative years of the Laboratory of Sensory Communication and later during the organization of the Institute for Sensory Research. He eventually became Administrative Director of the institute and, subsequently, Assistant Dean of the College of Engineering. In addition, he provided effective mathematical and electronic support for my theoretical work on the cochlea. His contributions are not nearly adequately reflected in published articles. I also should thank Robert L. Smith, who came to the institute as a graduate student and ended up by becoming its current director. He taught me animal surgery, more specifically, the surgery of the peripheral auditory system of Mongolian gerbil. I should also mention Gisle Djupesland, who joined me for a time to add his otological skills to my engineering ones in making acoustic measurements in the outer ear. I also received invaluable help in anatomy from Norma B. Slepecky and, in photomicroscopy, from Steven C. Chamberlain and his assistant, William P. Dossert. I should also thank several graduate and undergraduate assistants who contributed meaningfully to my research work and expanded it significantly. Their names appear in the text and in the references at the end of almost every chapter.

Finally, my deep appreciation goes to several technicians without whose help much of the experimental work would have been impossible. First of all, there was Bernhard Klock who manufactured the acoustic bridge for acoustic impedance measurement in the ear and also the prototype of the ear-like coupler for earphone calibration. He was followed by Michael W. Serafini, who made the string instrument for calibration of the stiffness of micropipettes used to measure the tectorial membrane compliance, and by Richard B. Mitchell, who made the precision drill for making accurate holes in the cochlear capsule. Of course, each one of them contributed other pieces of mechanical equipment, but the mentioned ones became the most important. On the electronics side, I first enjoyed the help of Robert Gardinier who made the hardware model of both the middle ear and the simplified cochlea. Next, I have to mention the outstanding work of Arthur J. Wixson who made the hardware model of the live cochlea and manufactured several pieces of electronic equipment, among them, the frequency discriminator that allowed us to produce efficiently transfer functions of various cochlear potentials. He has been followed by Dean J. Arpajian who wrote the final computer program for the cochlear model on the basis of the original program written by Earl J. Kletsky, having been aided at first by John F. Bruno and Michael S. Schechter. I should also thank Christos G. Stathatos Jr. for installing my computers and all around help with their use.

I also thank most sincerely Nicole M. Sanpetrino for her dedicated help with the manuscript, especially the graphic work, but also the final proofreading and formatting.

Last, but certainly not least, I thank my current wife, J. (Jagoda) Marie Zwislocki for her encouragement and constructive criticism coupled with the great happiness she has brought me.

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chapter

1

The Path of Sound

The substantive material of this introductory chapter should appear familiar to the reader of this monograph. It is included as a point of departure for the rest of the text in an effort to prepare the reader for what it contains and how it is organized. Nevertheless, certain statements may contain new information for any particular reader, depending on his or her background.

My research on sound transmission in the ear began with the inner ear, then moved to the middle ear, finally, to the outer ear for a short period of time. This order is contrary to the direction of sound propagation. But, as every electrical engineer who deals with networks and transmission lines knows, this is the correct order because the performance of every preceding stage depends on the input properties of the following one.

To be accurate, I should mention that my early research on the cochlea concerned only mathematical theory of postmortem preparations. No necessary empirical information was available for the live cochlea. My experimental and theoretical work on the latter did not begin until the 1970s, after my research on the middle and outer parts of the ear had been completed. This work was made necessary by new evidence indicating that not all the conclusions based on postmortem cochlear preparations were valid for the mechanics of the live organ.

Since the input properties of the sound transmitting parts of the ear have become known by now, it is possible to follow in this book the direction of sound propagation. This is done beginning with the outer ear all the way to the hair cells in the cochlea of the inner ear which, acting as microscopic microphones, transduce the mechanical vibration associated with sound into electrochemical processes culminating in nerve action potentials. The path does not stop at a dead end, however, because part of the generated electrochemical energy, enhanced by metabolic energy, is returned to the mechanical vibration through a positive electromechanical feedback. The first part of the path can be visualized best by looking at a longitudinal section of the outer and middle ear, as sketched in Fig. 1.1. The sketch also includes the fluid filled canals of the inner ear with a clearly visible spiral of the cochlea, its auditory part. Because in reality the human inner ear canals are embedded in hard bone, the artist had to mentally chip it away to show their course. The cochlear canal has been opened partially to show that it is divided longitudinally by a partition. The partition determines the mode of sound propagation in the cochlea. As shown in Fig. 1.2, it is not a simple structure but consists of a multilayered plate, called the basilar membrane,

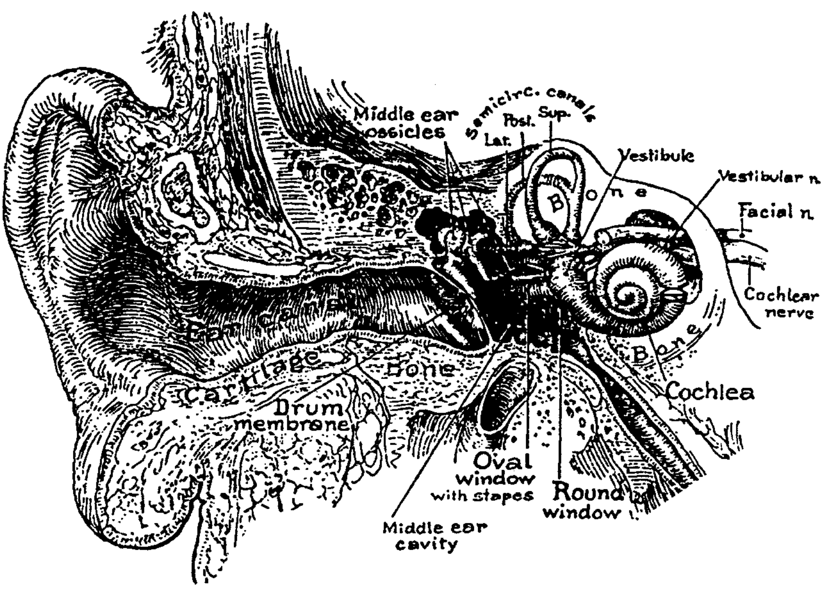

FIG. 1.1. Sketch of the longitudinal section of the outer and middle ear with visualized cochlea, which is opened at one location to indicate the inner partitions—the basilar and Reissner's membranes. (Modified from Brödel, 1946; cit. Zwislocki, 1984). Wever, E. G., & Lawrence, M: *Physiological Acoustics*. Copyright © 1954 by Princeton University Press. Reprinted by permission of Princeton University Press.

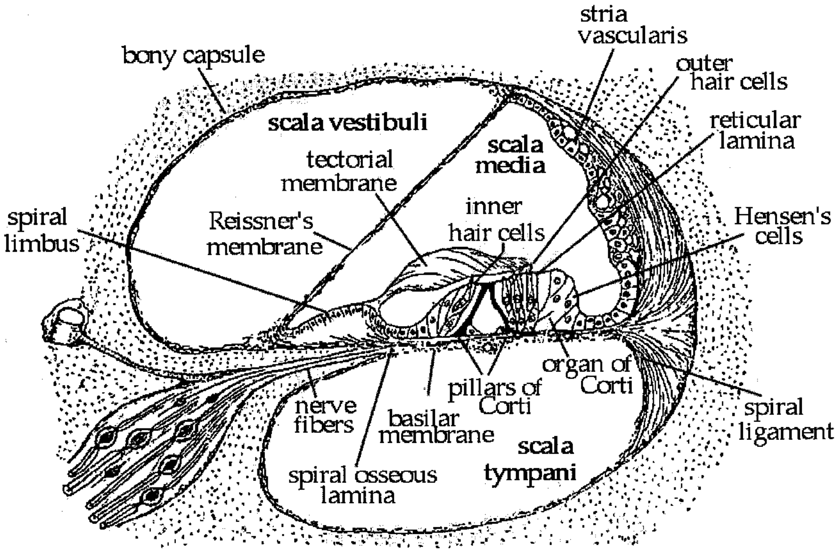

FIG. 1.2. Sketch of the cross section of the cochlear bony canal. (Modified from Rasmussen, 1943; cit. Zwislocki, 1984).

which supports a complex cell mass containing the sensory hair cells stimulated by its vibration. The partition with the hair cells is essential for hearing, and the analysis of its structure and function occupies a substantial part of this monograph.

When sound strikes the human head, most of its energy is reflected but some of it enters the auricle and the ear canal and is led to the tympanic membrane where, in the speech frequency range, about half of the incident energy is transformed into the vibration of the membrane and half is reflected again. From the point of view of auditory sensitivity, the two reflections and an added one in the concha of the auricle may appear as a waste of sound energy, but the reflections are used well by the nature. They serve to enhance the auditory sensitivity in certain frequency regions important in auditory communication. In addition, the reflections at the head and the auricle depend on the direction of incident sound and produce intensity and time differences between the two ears, enabling us to localize the source of sound.

The vibration of the tympanic membrane is transmitted to the three ossicles of the middle ear—the malleus, incus, and stapes, which connect the tympanic membrane to the oval window of the inner ear. The long process of the malleus, the manubrium, is embedded in the tissue of the tympanic membrane and increases its stiffness, improving in this way sound transmission to the ossicles. The malleus is connected to the incus through a massive joint that can be considered as practically rigid from the point of view of sound transmission, except at very high sound frequencies. When the manubrium is entrained by the vibration of the tympanic membrane, the first two ossicles rock around an axis determined in part by the ligaments that hold them in place and in part by their center of gravity, the latter becoming particularly important at high sound frequencies.

The long process of the incus is attached by a small cartilaginous joint to the stapes, which is the smallest bone in the human body. The rigidity of the incudo-stapedial joint appears to vary among mammalian species. According to indirect measurements, it seems to be practically rigid in guinea pigs, quite flexible in Mongolian gerbils and semirigid in humans. When the incus rocks, its long process pushes the stapedial footplate in and out of the oval window, where it is held by the annular ligament. In this way, sound is transmitted to the inner ear.

The advantage of the elaborate system of the ossicles and their rocking motion, as compared to a simple rod-like columella encountered in birds and amphibians, did not become clear until Békésy (1949) demonstrated that it is more stable in sound transmission and prevents certain distortions. It also acts as part of a mechano-acoustic transformer enhancing the sound pressure at the entrance of the inner ear relative to the sound pressure at the tympanic membrane, as was already pointed out by Helmholtz (1877) in mid-19th century.

It is not always clear that the air-filled cavities of the middle ear, which are in communication with the large volume of air in the pneumatic cells of the mastoid bone, play an important role in auditory sound transmission. In fact, they do not only provide a cushion of air necessary for an unimpeded vibration of the tympanic membrane but, as a result of their complicated geometry, also affect the dependence of auditory sensitivity on sound frequency. As I was able to demonstrate (Zwislocki, 1975), they combine their effects with those of wave reflections in the outer ear and those of ossicular mechanics to provide a surprisingly uniform sound transmission in the range of speech frequencies.

Sound is propagated in the outer ear in the form of compressional waves and, in the middle ear, through ossicular vibration. In the inner ear, the mode of sound propagation changes again and takes the form of transversal waves that run along the cochlear partition, somewhat like waves on the surface of water, as illustrated schematically in Fig. 1.3. It should be pointed out that the transversal waves are made possible by the round window of the inner ear, which is situated on the opposite side of the cochlear partition from the oval window. In the absence of the round window, vibration of the stapes would simply compress and decompress the inner ear fluid, producing little motion because of small compressibility of the fluid. The flexible membrane of the round window provides an easy release for the alternating pressure by allowing the cochlear fluid to oscillate between it and the oval window. Because the two windows are on its opposite sides, the cochlear partition is forced to participate in this oscillation. It is true that the helicotrema opening at the apical end of the cochlear canal provides a fluid passage between the two sides of the partition, but the cochlear waves do not reach it, except at very low sound frequencies, as illustrated. The wave pattern shown in the figure is consistent with a large number of measurements. It shows that the wave amplitude increases up to a maximum as the wave progresses toward the apex, then decays rapidly, whereas the wave length decreases continuously.

It has been established experimentally that the location of the maximum depends on sound frequency. For high frequencies it is near the oval window and moves away from it, toward the end of the cochlear canal, as sound frequency is decreased. Following a suggestion of Helmholtz's (1877, 1954), who predicted the existence of the maximum, its location has been believed to be the physiological code for the subjective pitch of sounds. Indeed, some measurements appeared to show a similarity between the ways the location and the pitch depend on sound frequency.

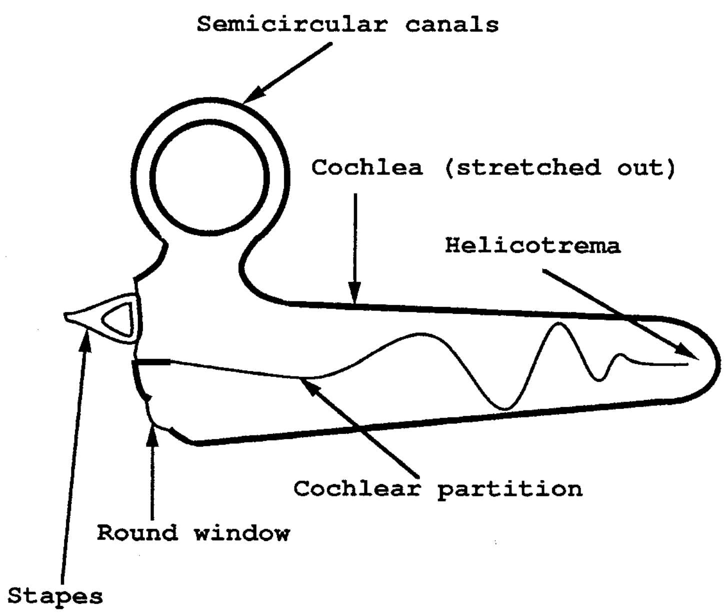

FIG. 1.3. Sketch of transversal waves on the cochlear partition, whose amplitudes are magnified.

The cochlear waves were first observed by Békésy in 1928 on postmortem preparations of human temporal bones and were investigated by him in greater detail in 1947. I explained their nature mathematically in terms of established physical laws, the first publication appearing in 1946, a more extensive one in 1948. These early discoveries are still valid in principle, but subsequent experiments on live animal preparations and associated theory have introduced important modifications. They revealed that the vibration maximum in a live cochlea is much sharper than after death, and that its location depends on sound intensity, so that it cannot be a direct code for pitch that remains practically invariant. They also revealed that the relationship between the vibration of the cochlear partition and the stimulation of the sensory cells is much more complex than originally assumed.

As the waves are propagated along the cochlea, the cochlear partition is deflected transversally back and forth at each location. The pattern of this deflection in the width direction approximates a rocking motion of the basilar membrane around an axis situated near the inner pillars of Corti. According to the classical theory, this motion produces a shear motion between the top of the organ of Corti, the reticular lamina that holds the hair cells, and the tectorial membrane that rotates around a different axis, the ridge of the spiral limbus. The shear motion, in turn, produces deflection of the hairs, or stereocilia, of the hair cells, leading to a depolarization of the hair cells and excitation of the nerve fibers that end on them.

In the following chapters, I analyze separately sound processing in each of the main parts of the sound-transmitting system of the ear. The analysis is based on my past work and, in part, constitutes its review and synthesis. However, much unpublished material is added, and the analysis is updated to coincide with the cutting edge of current research. This is particularly true for the cochlea whose function is so complicated that it defies comprehensive description in a journal article. Accordingly, I gave up on publishing exhaustively the results of my current research on the mechanics and electromechanics of the cochlea in journal articles and have reserved it for this book.

The outer and middle ear each occupy one chapter, but the cochlea occupies three, not only because of the volume of research it has commanded but also because it appeared to me that its complex function can best be explained in steps. Therefore, the first chapter in the sequence concerns the postmortem cochlea that is greatly simplified by comparison to the live cochlea. Once the principles of the simplified function are understood, it is easier to comprehend those of the more complex one.

The analysis of each part of the ear includes the following five aspects not necessarily in the order listed here: description of its structure, measurement of its dynamic characteristics, independent determination of its physical constants, construction of a mathematical, network—or even physical model and, finally, comparison of the model's characteristics with those measured on the natural system. The comparison has a double purpose—validation of the model, which is always a simplified cartoon of the real system, and determination of the effects of individual elements of the system. The extent to which the model characteristics agree with the natural ones may be regarded as a measure of our understanding of the system. Knowledge of the effects of the system's elements is not of purely academic value but can have applications to medical diagnostics, as became clear to me in particular on the occasion of my analysis of the middle ear function.

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chapter

2

The Outer Ear

Probably the most extensive investigations of outer ear acoustics were performed by E. A. G. Shaw (e.g., 1974) and his associates. My own work on the subject had a limited and practical purpose of developing a better acoustic coupler for earphone calibration. A working group of CHABA (Committee on Hearing Bioacoustics and Biomechanics of the National Research Council), which I chaired, decided that the available couplers were not entirely satisfactory and provided guidelines for the development of one that would be more up to date (Zwislocki et al., 1967). Since no laboratory picked up the challenge for a year or so and I needed a universal coupler that would allow me to calibrate various types of earphones with the same reference, I undertook the task myself. The development work extended on and off over 4 years, beginning in 1969. It required several kinds of measurements on the outer ear, which ultimately became useful in their own right. They complemented my earlier studies of the cochlea and the middle ear and helped me in accounting for the known dependence of auditory sensitivity on sound frequency. Here, I review these measurements and their analysis, which showed that the complicated geometry of the outer ear can be drastically simplified without appreciably changing its acoustic characteristics. This insight allowed me to design a coupler that lent itself to rigorous specification and was reasonably easy to manufacture.

MEASUREMENT OF SOUND PRESSURE TRANSFORMATION

To sufficiently specify the acoustic properties of the outer ear for our purposes, it was necessary to measure the sound pressure transformation between the tympanic membrane and several points along the ear canal and the concha. Pressure distribution across the ear canal was not investigated because, within the frequency range of our measurements, it was possible to assume that it was uniform. The assumption is permissible when the wavelength of sound is much greater than the linear cross sectional dimensions. At 10 kHz, the highest frequency used, the wavelength in the ear canal amounts to 3.52 cm, almost 5 times the canal's average diameter of about 0.75 cm.

Similar measurements were performed in the past, especially in the classical study of Wiener and Ross (1946), but we wanted to verify the older results and to be able to use the same instrumentation for comparative measurements on the natural ear and the coupler we were to develop. Our work was greatly facilitated by three circumstances—the presence of Dr. G. Djupesland, an internationally known otologist who was spending his sabbatical leave with me, the help of a clever machinist, and the availability of a mechanical adjustable arm for rigidly holding various instruments in the ear, which I had developed at Harvard and was allowed to take with me to Syracuse.

The measurements were described in two reports from my laboratory (Zwislocki,1970, 1971) and were summarized in two papers (Djupesland & Zwislocki, 1972, 1973). They were performed on 7 subjects—3 women and 4 men, whose ages ranged from 16 to 44 years old and who had normal hearing and no history of middle ear disorders. The appearance of their tympanic membranes and ear canals was normal by visual inspection.

A ½" probe tube microphone of Brüel and Kjaer with a probe tube of 5 cm length and 0.1 cm outer diameter, much smaller than the diameter of the ear canal, was used. The microphone was connected to associated Brüel and Kjaer electronics and held in the ear by means of the adjustable arm. It was attached to the arm through a calibrated micrometer-like screw arrangement that permitted precise insertion of the probe tube into the ear canal. The arm is described in greater detail in the next chapter. The business end of the setup is shown in Fig. 2.1, with the probe tube partially inserted into a subject's ear. At the beginning of an experiment, the microphone was positioned by hand so that the probe tube was over the entrance to the ear canal and oriented toward the tip of the manubrium of the malleus. The mechanical arm was made rigid by tightening its ball joints, and the probe tube was advanced until it gently touched the tympanic membrane. It was then lifted by 1 mm, and sound

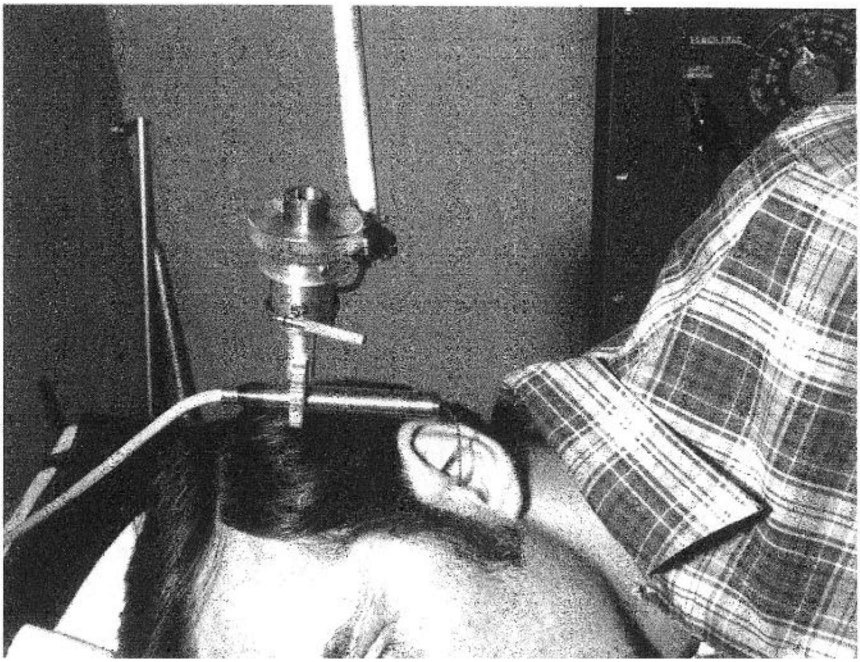

FIG. 2.1. Measuring microphone mounted on the adjustable holder with the probe tube at the entrance to the ear canal of a subject (Zwislocki, 1970).

pressure measurements over a frequency range from 0.2 to 20 kHz were performed. Each subject reclined on a small examination table, with his or her head turned sideways so that the right ear faced upward. The head was supported by a pillow filled loosely with cork chips and tied to the table by an adjustable belt. The arrangement steadied the head quite effectively. The experiments took place in a soundproofed booth with the inner-wall surfaces consisting of perforated plates backed up by sound absorbing material. The sound consisted of sinusoids produced by an Altec 405 loudspeaker mounted on a square baffle hanging over the subject's head. The distance between the entrance of the ear canal and the loudspeaker cone amounted to 110 cm. Because the measurements were comparative in nature, no absolute calibration of the sound generating and measuring equipment was necessary. Nevertheless, we ascertained that neither the sound field at the ear nor the probe tube had any pronounced maxima or minima in their frequency characteristics. In addition, we ascertained that the sound pressure measured by the microphone was transmitted from the tip of the probe tube by closing the tube opening with wax and measuring the resulting sound attenuation. The residual sound transmission was negligible.

Relative sound pressure was measured at three locations: (1) at a distance of 0.1 cm from the tympanic membrane at the tip of the umbo; (2) inside the ear canal, 1 cm from its entrance; (3) at the entrance; (4) at the tip of the tragus; and (5) 1 cm above it. The locations are illustrated schematically in Fig. 2.2. Sound pressure at the tympanic membrane served as reference. Because the relative sound pressure is quite sensitive to the location of measurement, a substantial effort was made to place the probe tip as precisely as possible. This was achieved by monitoring the placement with the help of a Zeiss surgical microscope. The probe tube was advanced within the ear canal by operating the screw arrangement of the mechanical arm until it reached the desired location. The first set of measurements was performed at 0.1 cm above the tip of the umbo. After its completion, the probe tube was withdrawn to make its tip coincide with the entrance of the ear canal. Subsequently, the tip was placed at 1 cm from the entrance inside the ear canal, then outside the ear canal at the tip of the tragus and, finally, 1 cm above it. Every measurement series was repeated 6 times in separate sessions, so that the probe tube was

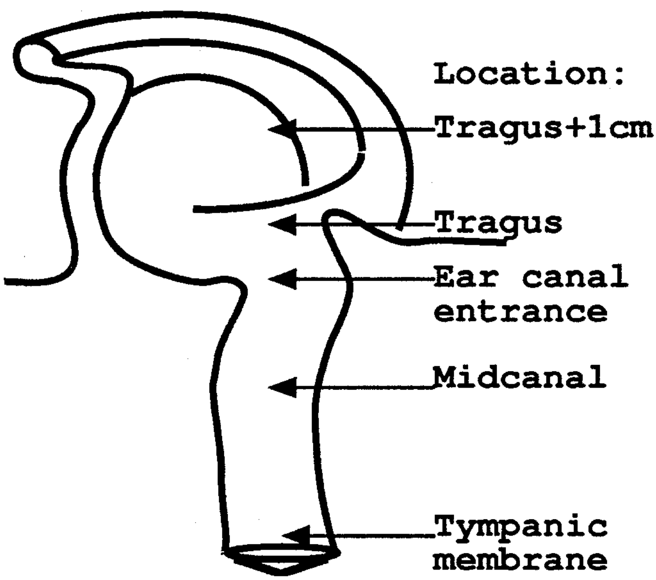

FIG. 2.2. Schematic of the acoustically crucial parts of the outer ear (after Shaw, 1974). From the External Ear by E. A. G. Shaw, 1974. In *Handbook of Sensory Physiology,* edited by W. D. Keidel and William E. Neff, New York: Springer-Verlag. Copyright © 1974 by Springer-Verlag. Reprinted with permission.

placed anew for every measurement. This procedure should have practically removed the effects of any error in the probe tube placement and in expected intra subject variability.

The careful placement of the probe tube tip at both ends of the ear canal allowed us to measure accurately the length of the ear canals of our experimental subjects. This length was defined as the distance between the tip of the umbo and the floor of the concha. The length was the same in all 3 female subjects, measuring 2.2 cm. It was more variable in the male subjects, extending from 2.2 to 2.5 cm, with a median of 2.4 cm and a mean of 2.38 cm. Thus, the average ear canal seems to be a little longer in men than in women. The average of the male and female medians comes to 2.25 cm and the overall mean, to 2.29 cm, which can be rounded to 2.3 cm. This is in agreement with previous results of Wiener and Ross (1946) and of Teranishi and Shaw (1968).

The group results of the sound pressure measurements are plotted in Fig. 2.3 as ratios (SPL differences) between the sound pressures measured at the tympanic membrane and at the other locations. Medians and interquartile ranges are used rather than means and standard deviations in an effort at better approximating typical values rather than average values. The latter may be appropriate for purposes of standardization, but the averaging procedure often eliminates characteristic details from measured functional relationships and can lead to misinterpretations of their underlying mechanisms by smoothing out relative maxima and minima of individual functions. In Fig. 2.3a are plotted the sound pressure ratios between the tympanic membrane and a location in the ear canal 1 cm away from its entrance, about 1.25 cm from the tympanic membrane. The maximum ratio corresponds to the quarter wave resonance of the ear canal portion between the tympanic membrane and the plane of measurement. Note the substantial variability reflected in the interquartile ranges, especially around the maximum. It stems from interindividual differences in the sound pressure ratios and in the frequency location of the maximum.

The sound pressure ratios between the tympanic membrane and the entrance of the ear canal are shown in Fig. 2.3b. The data are in reasonable agreement with the older data of Wiener and Ross (1946; see Djupesland & Zwislocki, 1972, 1973). The maximum is shifted to a lower frequency as a result of a greater distance between the tympanic membrane and the plane of measurement. Note again the very large variability around the maximum, particularly at its high frequency skirt, and the skewed distribution of the data in that region. Both are caused by the deviation of a small number of individual data from the median with respect to magnitude as well as to frequency. The frequency vari-

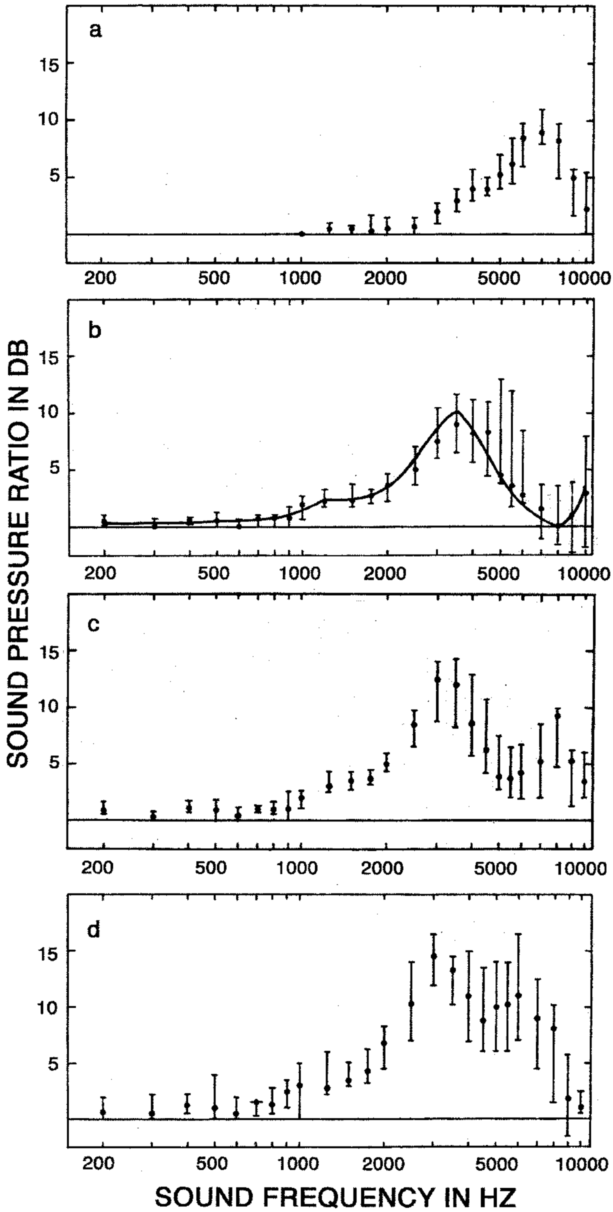

FIG. 2.3. Sound pressure transformation measured between the umbo location of the tympanic membrane and several locations in the outer ear: (a) ear canal, 1 cm from its entrance, (b) entrance of the ear canal, (c) the tragus, (d) 1 cm above it. Closed circles indicate the population medians, and the vertical lines the interquartile ranges. The continuous line in (b) indicates medians obtained after normalization of all sound frequencies to the maximum response.

ability must have had the effect of broadening the apparent width of the maximum so that the maximum does not match any typical pattern. To gain a measure of the effect, the median frequency of the peak was determined, and the individual data normalized with respect to it. The medians of these normalized data are plotted by means of the smooth curve. A slight shift of the maximum toward a lower frequency and a slight increase in its size appear to be the main effects of the normalization. The expected increased sharpness of the maximum is not clearly apparent because it is reflected mainly in the increased height of the maximum.

The sound pressure ratios between the tympanic membrane and the two locations outside the ear canal—at the tragus and 1 cm beyond it, are shown in Fig. 2.3c and Fig. 2.3d. A second maximum at a higher frequency has been added to the first, and the first has been shifted a little more toward lower frequencies. Both phenomena can be ascribed to a further increased distance of the measuring plane from the tympanic membrane, which lowered the frequency of the quarter-wave resonance and made a three-quarter wave resonance possible around 8 kHz. Also, the quarter-wave resonance of the concha additionally increased the sound pressure ratio in the vicinity of 4.5 kHz (Teranishi & Shaw, 1968). According to Fig. 2.3d, the various resonances appreciably enhance the sound pressure at the tympanic membrane relative to the sound pressure just outside the ear in the broad frequency range between about 2 and 8 kHz. This has a beneficial effect on auditory sensitivity.

In many natural listening conditions, the source of sound is located in front of the listener's head at a sufficient distance so that conditions of a free sound field are approximated. In this situation, sound reflection and diffraction at the listener's body and head contribute to sound pressure transformation between the sound source and the tympanic membrane. The total sound pressure transformation is somewhat awkward to measure directly, but it can be obtained by adding the SPL transformations between the source and the entrance to the ear canal and to that in the ear canal. The results of two different computations of the total transformation are compared in Fig. 2.4. One (thick solid line) was obtained by combining Djupesland's and my measurements of the transformation in the ear canal (thin dashed line) with the measurements of the body and head effects (thin solid line) performed by Wiener and Ross (1946). The other (thick dashed line) was provided by Shaw (1974) as a weighted average of data contributed by several investigators. Because the difference between the two resulting curves does not exceed 2 dB, we may be confident that the total transformation is reasonably well established.

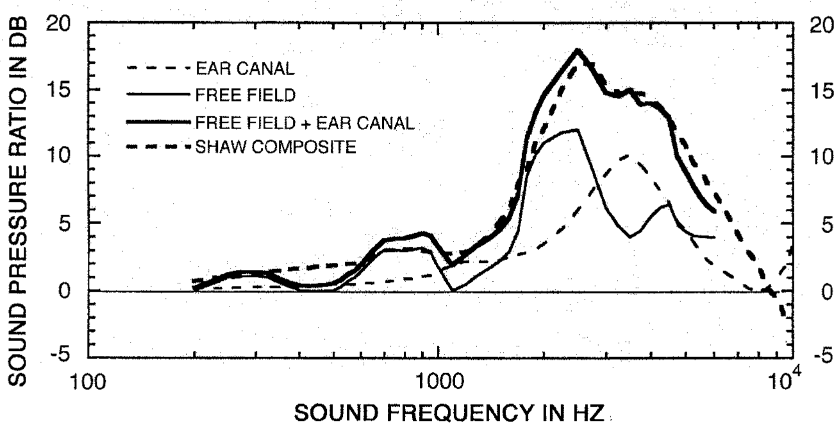

FIG. 2.4. Sound pressure transformation between the free sound field and the tympanic membrane. The thick solid line is a composite of the ear canal measurements of Djupesland and Zwislocki (1972, 1973) and the body and head effects measured by Wiener and Ross (1946). The thick dashed line was obtained by Shaw (1974) as a weighted average of several sets of measurements by several authors.

MODELING THE OUTER EAR ACOUSTICS

One purpose of modeling the acoustics of the outer ear is to find out how far the complicated shape of the outer ear can be simplified without intolerably affecting its acoustic characteristics. My modeling efforts were performed in two steps. First, the pressure distribution in the ear canal was modeled with the help of an electrical network analog (Zwislocki, 1965, 1970); second, the acoustic characteristics of both the ear canal and the auricle were simulated with the help of a mechanical model. The latter effort led to the development of a coupler for earphone calibration (Zwislocki, 1970, 1971, 1980) called *ear-like coupler* or *ear simulator.*

For the modeling purposes described here it is necessary to introduce acoustic variables that are analogs of electrical network variables. This set of variables can be found perhaps the most conveniently in H. F. Olson's *Dynamical Analogies* (1958). According to the theory of electroacoustic analogies of the first kind, the acoustical analog of an electrical capacitance, C_e, is an acoustical compliance, C_a; the acoustical analog of an electrical inductance, L, is an acoustical inertance, M; and the acoustical analog of an electrical resistance, R_e, is an acoustical Resistance, R_a. Furthermore, sound pressure, p, is an analog of the electrical voltage, v, and the volume velocity, √ (displacement of a volume of fluid per unit of time), an analog of electrical current, i. The amplitudes of the latter variables, which in general depend on time, are denoted by capital letters—P, √, V and I. Finally, the acoustical input impedance, $Z_a = P/\surd$, is an analog of the electrical input impedance, $Z_e = V/I$. Additional variables are introduced in further text as needed.

To find connections between the acoustical variables introduced above and the geometrical dimensions of an acoustical system, we must introduce appropriate mathematical formulas. The connections arise from the theory of acoustical waves and are given here without mathematical derivations, which can be tedious. The acoustical compliance is defined as $C_a = V/\rho_o c^2$, where V is the static volume of fluid in an enclosure; ρ_o, the density of the fluid (e.g. air) at rest; and c, the velocity of wave propagation in the fluid. The effect of an acoustical inertance is produced by constrictions through which the fluid must flow, or relatively narrow tubes. The defining formula is $M = \rho_o l/\pi r^2$, where ρ_o has already been defined; l is the effective length of the tube; π has the usual meaning; and r is the effective radius of the tube. It should be noted that the effective length, l, of a tube is somewhat larger than the geometric length and that, in the case of a tube with a circular cross section, the effective radius, r, is equal to the geometrical one.

The next step in modeling the acoustics of the outer ear is to determine the relevant geometrical dimensions. The most obvious one is the length of the ear canal. As already mentioned, this length was determined automatically by placing the probe tube with the help of a calibrated micrometer-like screw. A group of 7 subjects was involved, 4 male and 3 female. The length of the male ear canals ranged from 2.3 to 2.5 cm with a median of 2.3 cm. The female ear canals were all 2.2 cm long. Although the population sample was small, and a definite conclusion cannot be reached, there appears to be a disparity between the two populations. As its result, and because of similar disparities in other dimensions, models of a typical male ear should have different parameter values from models of a typical female ear. Strictly speaking, every individual ear requires different parameter values, and a model based on typical dimensions may not represent any natural ear at all. Nevertheless, the approximation is close enough to be useful in many measurements and for an understanding of the fundamental processes. With this justification in mind, I have averaged the dimensions of the male and female ears. For the length of the ear canal, the average of the male and female medians is 2.25 cm. This figure is in excellent agreement with Wiener and Ross's (1946) results and with the value accepted by Teranishi and Shaw (1968) on the basis of acoustic measurements.

We need two additional dimensions of the ear canal—its volume and its average cross-sectional area. Because of the irregular shape of the ear canal the latter is not easy to determine directly. A partial volume of the ear canal was determined on the occasion of acoustic impedance measurements at the tympanic membrane (e.g., Zwislocki, 1957a, 1957b). Perhaps the most accurate measurements were achieved during measurements with the acoustic bridge (e.g., Zwislocki, 1963; Zwislocki & Feldman, 1970). Because of the configuration of the speculum in which the bridge was held and the shape of its sealing tip, the insertion depth remained approximately constant in all ear canals. It amounted to approximately 0.8 cm. This left a residual length of 1.45 cm in a median ear canal. The volume of air associated with this length was measured by filling it with alcohol by means of a calibrated syringe (e.g., Zwislocki, 1957a, 1957b). The particular results used here were obtained on 10 male and 12 female subjects (Zwislocki & Feldman, 1970). The median residual volume came out to be 0.70 cc for the male ears and 0.58 cc for the female ears. The mean of these two median values is 0.64 cc and does not deviate substantially from the grand mean of the population, which was found to be 0.67cc. The median cross-sectional area of the ear canal can be obtained by dividing the median residual volume by the residual length. A value of 0.44 cm^2 is found. It leads to an average median diameter of 0.748 cm, a value only 7% larger than the value estimated by Békésy and Rosenblith (1951) and accepted by Teranishi and Shaw (1968). Extrapolating to the full length of the ear canal, the volume becomes 0.99 cc, practically, 1 cc, again, in excellent agreement with Békésy and Rosenblith.

For modeling the acoustics of the concha of the auricle we need dimensions analogous to those determined for the ear canal (Zwislocki, 1970). As derived from Delany's (1964) acoustic measurements and his network modeling, the air volume of the concha approximates 4.28 cc and the equivalent volume of the ear canal and the middle ear, 1.81 cc, together, 6.09 cc. The latter figure is very close to that assumed for certain standard couplers for earphone calibration (e.g., Beranek, 1988), which is 6.0 cc. Accepting that the 6 cc figure is correct, we can subtract from it the 1 cc volume of the ear canal and the equivalent volume of the middle ear of 0.65 cc (e.g., Zwislocki & Feldman, 1970) to obtain for the concha 4.35 cc, in reasonable agreement with the value derived from Delany's work. We measured the depth of the concha directly on 6 people and found a rather constant value of 0.9 cm. Approximating the concha by a cylinder, the two values can be used to calculate its average diameter. The resulting value is 2.48 cm, which agrees almost exactly with the outer rim of the coupler for earphone calibration suggested by Delany and his coworkers (Delaney, Whittle, Cook, & Scott, 1967).

The ear canal can be modeled according to the theory of electroacoustic analogies in terms of a lumped element electrical transmission line. Such a line is shown in Fig. 2.5. It contains two sections, one corresponding approximately to the outer part of the ear canal, which accommodates various ear devices, the second remaining free. The network acts as a low pass filter, and its elements have to be chosen so that the cut-off frequency remains outside the range of interest. Four equations are available to achieve this and to match the electrical characteristics of the line to the acoustical characteristics of the ear canal. The first two define the characteristic impedance of the ear canal and the corresponding characteristic impedance of the electrical transmission line:

$$Z_a = \rho_o c/A \qquad Z_e = (L/C_e)^{1/2} \tag{2.1}$$

The symbols have already been defined, except for A, which means the average cross-sectional area of the ear canal and C_e, which means the electrical capacitance. The third equation defines the cutoff frequency:

$$f_c = 1/\pi\ (LC_e)^{1/2} \tag{2.2}$$

Finally, the fourth gives the total acoustical capacitance of the ear canal, corresponding to the total canal volume:

$$C_{at} = V_t / \rho_o c^2 \tag{2.3}$$

Combining these equations we obtain the defining equations for the electrical network elements:

$$C_e = 1/\pi\, f_c Z_e \tag{2.4}$$

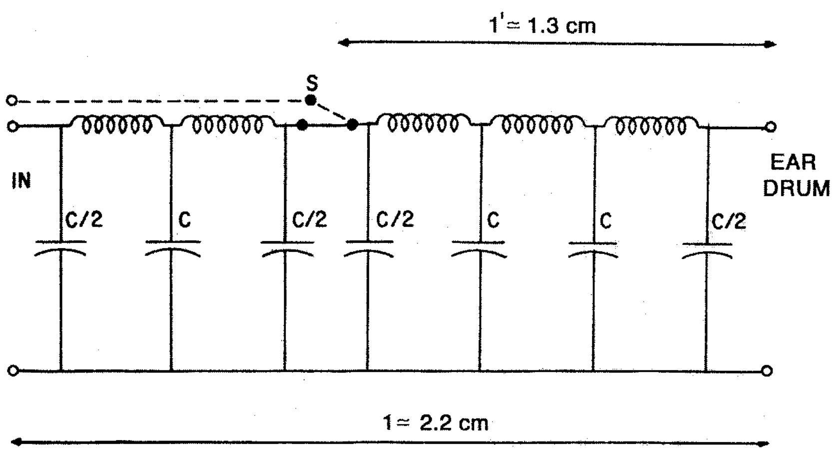

FIG. 2.5. Network analog of the ear canal. The switch, S, marks the location of the tips of most ear inserts (Zwislocki, 1970).

$$\mathbf{L = C_e Z_e^{\,2}} \qquad \mathbf{2.5}$$

$$\mathbf{n = C_{at}/C_a} \qquad \mathbf{2.6}$$

Note that, if $Z_e = Z_a$, then numerically, $C_a = C_e$.

The numerical values of the constants C_e, L and n can be calculated as follows. For a temperature of about 34° C prevailing in the ear canal (Lilly, 1970, personal communication), the density of air is $\rho_o = 1.15 \times 10^{-3}$ g/cm^3 and the sound velocity, $c = 3.52 \times 10^4$ cm/sec. Together with the cross-sectional area of the ear canal, $A = 0.44$ cm^2, these numerical values lead to a characteristic acoustic impedance of the ear canal, $Z_a = 92$ acoustic Ohms (dyne sec/cm^5). In the MKS system, these values become: $\rho_o = 1.15$ Kg/m^3; $c = 3.52 \times 10^2$ m/sec; $A = 0.44 \times 10^{-4}$ m^2; and $Z_a = 9.2 \times 10^6$ Newton sec/m^5, respectively. On the basis of preliminary calculations, we select for the cut-off frequency $f_c = 24.5$ KHz. Together with the Z_e value already determined, this leads to a $C_e = 0.14$ µF and an $L = 1.2$ mH. The number of sections becomes $n = 5$. These numerical values specify entirely the electrical network analog of the ear canal.

To test the adequacy of the analog, we can measure the voltage transformation between its input and its load at the other end. The voltage transformation should agree with the corresponding sound pressure transformation in the ear canal. In the latter, the acoustic impedance at the tympanic membrane defines the load. As a consequence, the network analog has to be terminated by an electrical analog of this impedance. Such an analog was obtained by developing a network analog of the middle ear, as described in chapter 3. If, after loading the ear canal analog with the analog of the middle ear, a correct voltage transformation is obtained, we can conclude that both analogs, that of the ear canal and that of the input impedance of the middle ear, are satisfactory. The voltage transformation is compared with the sound pressure transformation in Fig. 2.6. The former, plotted as a function of sound frequency, is shown by the solid line, the latter by the closed circles. The crosses indicate the voltage transformation when the ear canal analog is loaded by a simple resistance of 300 Ohms. Note that the peak transformation is about the same for both the middle ear load and the resistive load but that the width of the peak is greater with the former. This seems to be due to the reactive component of the middle ear impedance. As is shown in chapter 3, the middle ear impedance is purely resistive at the location of the peak of the sound pressure transformation but is capacitive (negative) at lower frequencies and inductive (positive) at the higher ones. Capacitive impedance has the effect of lowering the frequency of the resonance peak, inductive impedance, of increasing it. As a consequence, an impedance that is capacitive below the frequency of

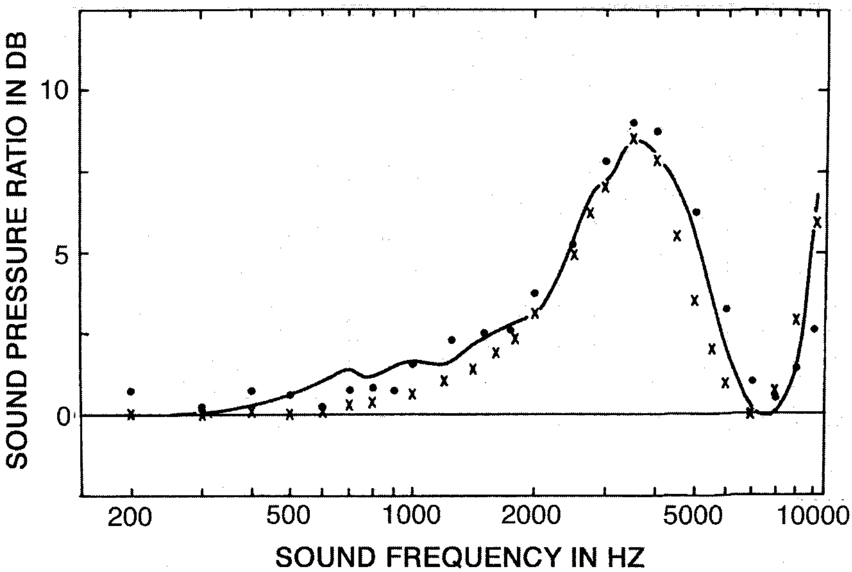

FIG. 2.6. Voltage transformation in the network model of the ear canal, when terminated by the network model of the middle ear (solid line) and by a 300 Ohm resistance (crosses), compared to sound pressure transformation measured in the ear canal between the tympanic membrane and the canal entrance (Zwislocki, 1970).

the peak and inductive above it has the effect of broadening the peak. A broader peak may be expected to be beneficial for the sensitivity of hearing, and the match between the length of the ear canal, which determines the frequency of the peak, and the nature of the middle ear impedance in its vicinity suggest an exquisite piece of evolutionary adaptation.

One additional way of testing the model results is to calculate the sound frequency of the peak from wave theory, more specifically, from the theory of wave reflections. The ear canal is modeled by a uniform tube closed at one end but open at the other. According to the theory, the lowest wave resonance occurs when the effective length of the tube is equal to a quarter wave length, so that

$$\lambda/4 = l + 0.411D \tag{2.7}$$

where λ is the wave length, l, the geometric length of the tube, and D, the diameter of the tube. Because l and D are known, λ can be calculated and from it the frequency of the resonance peak. This frequency is simply $f = c/\lambda$. With the numerical constants already given, the predicted frequency of the lowest resonance peak becomes f = 3.441 KHz, in excellent agreement with the model data. It should be pointed out that, if the impedance of the middle ear deviated from pure resistance at the resonance frequency, this frequency would have been shifted and no close agreement would have been found.

Because, according to Fig. 2.6., an electrical transmission line based on a uniform, straight tube adequately simulates the sound pressure transformation in the ear canal, it appears permissible to model the rather convoluted ear canal with such a tube. This leads to great simplification in constructing an acoustic ear simulator, and the straight tube approximation has been attempted for the concha as well. The resulting configuration is shown in Fig. 2.7. It includes, in addition, a damped resonance system simulating the mechanical properties of the auricle.

The ear simulator shown in the figure consists of two main parts—an upper part containing simulators of the auricle, concha, and the outer part of the ear canal, and a lower part simulating the inner part of the ear canal

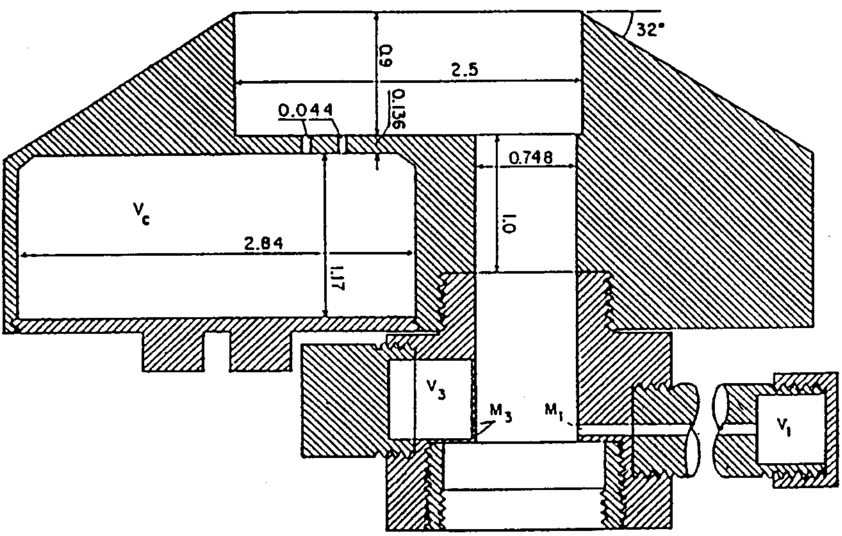

FIG. 2.7. Technical drawing of the ear simulator. From top to bottom, the cavities represent the concha cavity with a large cavity coupled to it through two narrow tubes, the ensemble mimicking the impedance of the auricle, and the ear canal. The enlargement at the bottom fits the measuring microphone. The tubes M_1 and M_3 leading to the cavities V_1 and V_3 constitute 2 of the 4 resonators mimicking the impedance of the middle ear. The bottom part of the simulator can be detached at the horizontal line through the ear canal cavity for calibration of insert phones and other insert devices. This part has been standardized under the designation of *occluded ear simulator* (ANSI S3.25-1979; Zwislocki, 1970).

and the acoustic impedance of the middle ear (Zwislocki, 1970, 1971). This part also includes at the bottom a receptacle for the Brüel and Kjaer 0.5 inch microphone. The dimensions of the concha and ear canal cavities have been already given previously. However, the length of the ear canal had to be adjusted to take into account the temperature difference between the natural ear canal and its simulation and also the equivalent volume of the microphone. The length was reduced from 2.25 cm to 2.15 cm. The circular outer shape of the coupler at the top was made to match the shape proposed by Delany and his coworkers (1967). The large cavity under the concha cavity, marked V_c, and the two small openings coupling it to the concha cavity were designed to simulate the acoustic impedance of the auricle according to measurements of Ithell, Johnson, and Yates (1965). This impedance affects the sound pressure generated by an earphone in the ear canal only at sound frequencies below 0.5 KHz. Note that the ear canal opens into the concha cavity near its side wall, like in the natural ear, rather than in the middle. This is essential because of the transversal resonance modes of the concha. The lowest such mode is illustrated in Fig. 2.8. The concha and the entrance of the ear canal are schematized by the thick lines, the sound pressure distribution, by the shaded areas. Note that the sound pressure has a null in the middle of the simplified concha and a maximum at the location of the ear canal indicated by the opening in the concha floor. Thus, the eccentric location of the ear canal avoids a null in sound transmission to the tympanic membrane and produces maximum sound pressure at the entrance to the ear canal.

The lower part of the simulator contains four side branches situated right above the microphone receptacle. Two of these branches are visible in the longitudinal median section of the simulator. The other two are at right angles to the plane of the drawing. The side branches consist of damped

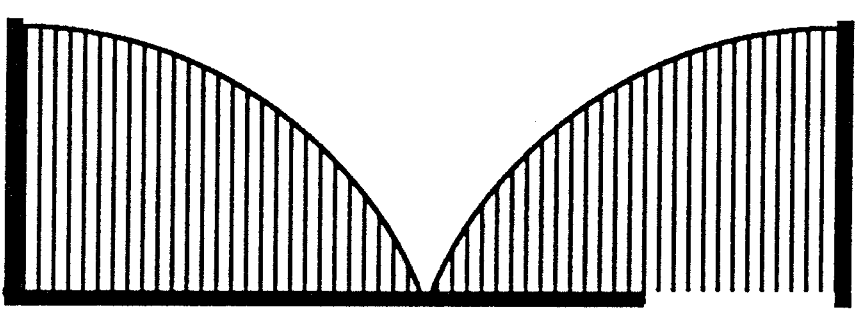

FIG. 2.8. Schematic representation of the first transversal mode of sound pressure distribution across the concha. The heavy lines indicate the walls of the simplified concha; the gap between them at the bottom indicates the ear canal entrance.