The coiled structure of the cochlea is revealed in an electron micrograph. Located within its coils are the auditory cells (orange – the membranes surrounding the cochlear canals are partially torn; this occurred during the preparation process for this photograph).

IMAGE: SCIENCE PHOTO LIBRARY / FURNESS, DR. DAVID

HEARING BY LIGHT

TEXT:
CATARINA PIETSCHMANN

Talking with friends, enjoying a concert, talking on the phone on noisy streets – people with hearing problems are often unable to hear things that others can. Tobias Moser aims to make sound accessible to those with hearing disabilities in a whole new way through a new generation of hearing protheses. Known as optical cochlear implants, these devices serve as an example of therapies developed on the basis of fundamental research.

Some 16 million people living in Germany suffer from a hearing impairment, and about 80,000 are deaf. Approximately two out of every one thousand children are born with a hearing impairment that until now has been irreversible; others develop a hearing impairment during the first few years of their life. Those born with little or no hearing have trouble learning to speak vocally, or remain unable to, impairing their ability to communicate with the people around them. Their social life suffers as a result.

Tobias Moser is a neuroscientist and otolaryngologist who heads a research group at the Max Planck Institute for Multidisciplinary Sciences in Göttingen, and the Institute for Auditory Neurosciences at the University Medical Center Göttingen. Moser is a specialist for synaptic hearing loss, which is an inner ear hearing disorder for which hearing aids are typically ineffective. At present, the only option for an infant suffering from synapse hearing loss is to have a cochlear implant to enable it to hear and speak later in life. Such an implant will ideally be implanted in the first year of life, before the child begins to speak. "Many synaptic connections in the brain expand and change during the first years of life," Moser explains. "If during this phase of development, the brain does not receive enough auditory stimuli transmitted from the ears, many such synaptic connections will not be made correctly. This deficit is difficult or impossible to compensate for later."

Our sense of hearing is complicated. Sound waves are conducted from the auricle into the outer ear canal and on to the eardrum, where they are picked up by the ossicles of the middle ear – the malleus, incus, and stirrup – and passed on to the spiral-wound cochlea in the inner ear. "Up to this point, microsurgery has been so successful in treating disorders with impaired sound transduction that the patient doesn't even need a hearing aid," says Moser. However, in 70 percent of cases the cause of hearing loss lies in the inner ear or auditory nerve.

Transmission to the inner ear

The spiral-shaped cochlea in the inner ear features four rows of sensory hair cells; their hair bundles protrude into the fluid-filled interior of the cochlea. Sensory tissue is set in motion by the mechanical vibrations transmitted to the cochlea from the ossicles, thereby deflecting the hair bundles of the sensory cells by the tiniest fraction of a millimeter. That suffices to activate the sensory hair cells. The outer three rows of sensory hair cells amplify these mechanical vibrations for faint sounds. The inner row transmits the sound information from its synapses to auditory nerve cells, which carry the information to the brain as a series of nerve impulses. Every individual is born with a limited number of sensory hair cells and auditory nerve cells. These have to last a lifetime, as the body cannot replace them. "Noise and age are the probable main causes for hair cells, synapses and, eventually, auditory nerve cells dying off," Moser explains. When exposed to 100 decibels or more for long time, at a disco club, for example, sensory hair cells are likely to be damaged or destroyed. Furthermore, some antibiotics or cancer drugs can cause hearing loss, which may be temporary or permanent.

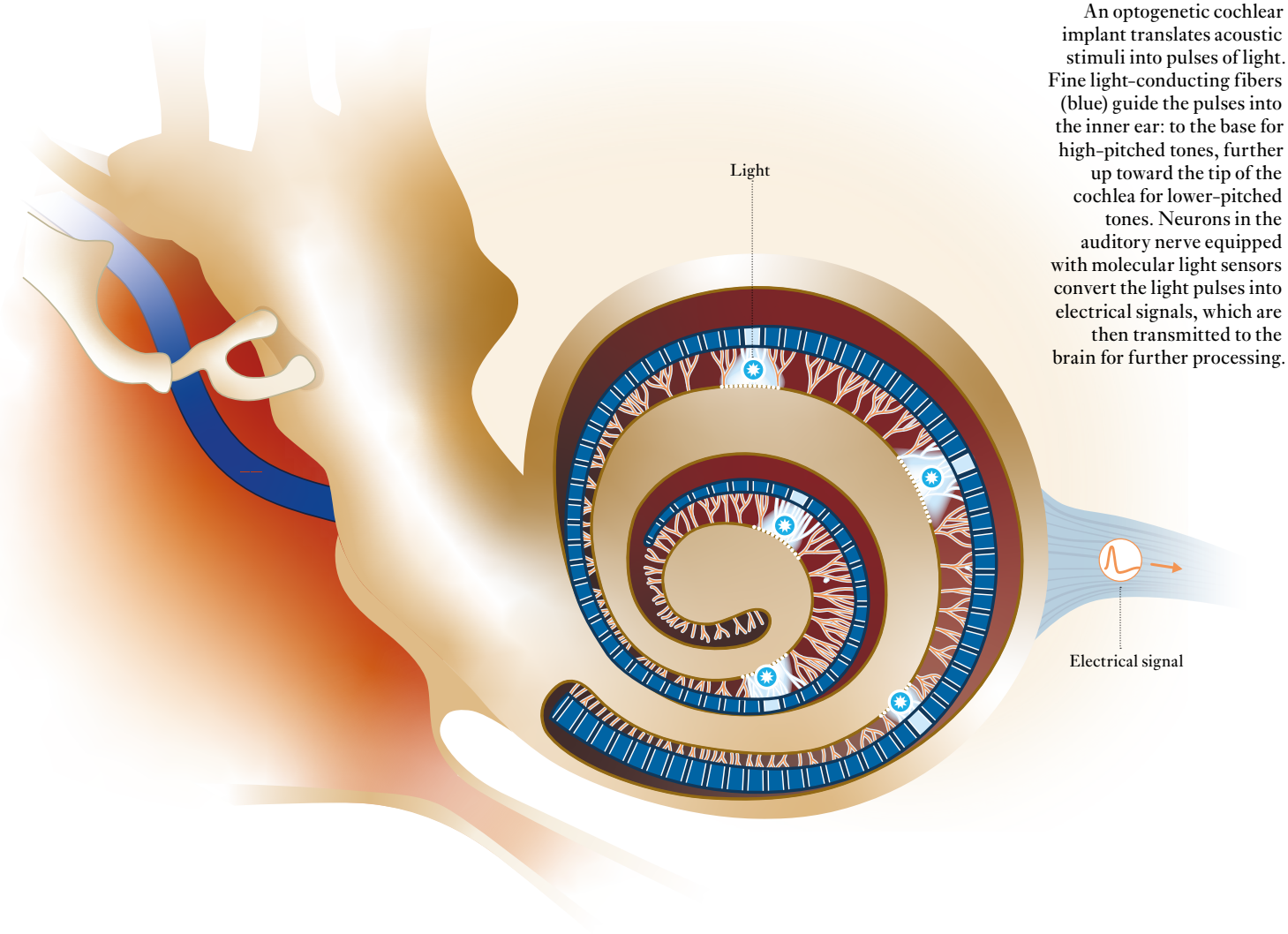
Cochlear implants are used for children who are born deaf as well as for adults who develop profound hearing loss or deafness. These implants take over the function of the cochlea, bypassing the sensory cells to directly stimulate the auditory nerve cells. In the surgical procedure, an electrode carrier with 12 to 24 electrodes (depending on the model) is implanted into the cochlea, and an electrical stimulator with receiving coil and magnetic coupling is placed in the temporal bone behind the ear. A speech processing unit inductively linked to the implanted device breaks down sound into its various frequencies and then transmits frequency, time, and volume data to the stimulator. The patients have to relearn how to hear using the cochlear implant because the artificial signal provided to the nerve is rather limited. "Many patients say they perceive a whooshing, metallic sound at first." Moser describes patients' initial impressions after the surgery as follows: "Speech is often difficult or impossible for them to understand. It may, for example, sound like someone is talking to them from behind a wall: they can hear that someone is saying something, but are unable to understand what. Even after months of practicing, in many cases it is still hard for patients to tell the difference between a spoken question and a statement, as they are unable to perceive the intonation of what was said."

SUMMARY

Hearing impairments stemming from the inner ear can be partially corrected using a cochlear implant. Researchers are currently developing optogenetic implants to afford a better hearing perception than is possible with today's electrical implants.

A new generation of optical cochlear implants will be able to transmit more frequencies for improved hearing. The first human trials are slated for 2026.

The patient and his/her relatives always have extensive consultations with doctors, engineers, and speech therapists before undergoing the operation. "Those unwilling or incapable of practicing intensively for a year or more should not go for an implant," says Moser. But even after doing intensive listening training, things never get back to the way they used to be. "The patients will always have difficulty understanding speech in everyday situations where there is background noise, and/or with multiple conversation partners. Melodies are also difficult for them to recognize." After insertion of a cochlear implant, the auditory experience of listening to a Sergei Rachmaninoff piano concerto or a Whitney Houston song will not be the same at all.



An optogenetic cochlear implant translates acoustic stimuli into pulses of light. Fine light-conducting fibers (blue) guide the pulses into the inner ear: to the base for high-pitched tones, further up toward the tip of the cochlea for lower-pitched tones. Neurons in the auditory nerve equipped with molecular light sensors convert the light pulses into electrical signals, which are then transmitted to the brain for further processing.

CHART: GCO ACCORDING TO MOSER / INSTITUTE FOR AUDITORY NEUROSCIENCE

At his office at University Medical Center Göttingen, Moser frequently talks to patients who are unsatisfied with the results they are getting from "electrical hearing". Such a problem can be a source of despair for professional musicians in particular. Moser's hope, then, is that the optical cochlear implants his research team has been working on since 2007 will be a success. The concept is to have sound information transmitted by light rather than electrically as light can be better confined in space promising better frequency selectivity. If feasible, this technology would truly be a breakthrough, rendering the audial perception of speech and music much more natural and rich in nuance.

The work of researchers at the Max Planck Institute for Biochemistry in Martinsried laid the foundations for this technology back in the 1970s, when Dieter Oesterhelt and his team discovered ion pumps within the cell membrane of bacteria which are activated by light. Then, around the turn of the millennium, Peter Hegemann of the University of Regensburg (now at Humboldt University of Berlin) in collaboration with Georg Nagel (now at the University of Würzburg) and Ernst Bamberg discovered light-sensitive ion channels in green algae while working at the Max Planck Institute for Biophysics in Frankfurt. These channels form the basis for optogenetics, a new research field that is enabling advances in how scientists unravel the mysteries of how cells and organs work. Optogenetics are of particular use in neurosciences. Outside of the eye, nerve cells are insensitive to light. In order for these cells to be activated by light, they first have to be equipped with a corresponding sensor. The light-sensitive ion channels originally deriving from algae cells are utilized for this purpose. Researchers first introduce the genetic blueprint for these proteins into the nerve cells of the auditory nerve via gene therapy techniques. Harmless, non-reproductive viruses are utilized as gene shuttles, which bind exclusively to the nerve cells in the auditory nerve and then place the gene for the channel protein in the cell nucleus of the nerve cell. The nerve cells then integrate the light sensor into their membrane. When the sensor detects light, it opens its floodgates so that ions flow in, electrically activating the cell. As with a conventional electrical cochlear implant, sound is broken down into frequency bands –

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but many more and finely defined ones in this case. Sixty-four optical fibers corresponding to the frequency bands then conduct light into the inner ear, with high frequencies fed to the base of the cochlea and lower frequencies further along the coils of the cochlea to its tip. "The brain knows that activated nerve cells at the base of the cochlea mean high-pitched sounds, and that activated cells at the end mean low-pitched hums. All we have to do, then, is ensure that the optical fibers attach to the right places on the cochlea to activate the nerve cells matching the particular sound," Moser elaborates. These implants thus deliver an auditory perception even when there are no more intact sensory cells left.

Pitch differences are easily distinguishable

Initial testing via computer simulation and trials with rodents has demonstrated that the technology works. At low and medium volume levels, frequency selectivity is near to that of normal hearing. Now Moser and his team intend to test out the new implants on common marmosets at the Primate Center in Göttingen. These monkeys are real chatterboxes, much like humans are, which plays into research. Marmoset calls are played from a loudspeaker, which only has as many frequencies as an optical cochlear implant is capable of. "Despite the limited frequencies, the monkeys recognize the calls and respond, which suggests that new implants can communicate communication sounds in an understandable way," says Moser. As the next step, the research groups led by Marcus Jeschke, a junior research group leader at Göttingen, intend to insert optical cochlear implants in monkeys to find out whether they are still able to recognize calls from their fellow monkeys.

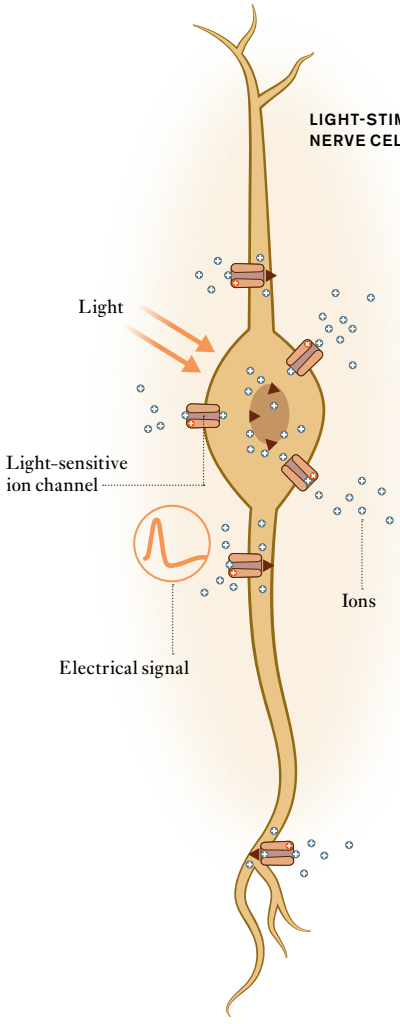
Moser and his team will have to fine-tune the technology before initial human clinical trials can commence in 2026. The implants' energy consumption needs to be reduced, and time and frequency resolution need to be optimized. There is one person who will be particularly happy when the trials start, even if he cannot take part in them himself: Fadhel El May, one of the doctoral researchers working with Tobias Moser. Hearing-impaired from birth, El May grew up wearing hearing aids. Then at the age of sixteen, he received an electrical cochlear implant.

We asked him about how the implant changed his life. "At first, I was shocked at how little I was able to understand. But after six months, my brain became able to understand language. If I were to switch off the implant today, I would be totally unable to follow a group conversation," relates El May, who studied engineering in Lausanne and Boston. Now able to follow discussions in larger groups, he still prefers talking one-on-one. "It's exhausting to me when there are multiple people talking at the same time. I sometimes will just have to leave the conversation."

He doesn't want to get a cochlear implant for his other ear, as he explains: "My hearing is worse in the ear with the hearing aid than in the ear with the implant, but when listening to music I am able to enjoy rich sound and hear high frequencies. I wouldn't want to give that up!" El May has now started taking piano lessons, and the only difficulty he has encountered is that he is unable to hear the difference between chords and individual notes, making him unable to correct an improperly played chord. Despite their drawbacks, cochlear implants have at least one small advantage over natural hearing: El May can use them as headphones. The implant automatically connects to his smartphone via Bluetooth, allowing him to make phone calls undisturbed by ambient noise, because he has his "EarPod" right in the ear itself.

www.mpg.de/podcasts/sinne (in German)

CHART: GCO ACCORDING TO MOSER / INSTITUTE FOR AUDITORY NEUROSCIENCE



In order for an auditory nerve cell to perceive light pulses and transmit the information contained therein via aural impression, the cell has to be genetically modified so that it produces light-sensitive ion channels and integrates these into its cell membrane. Electrically charged atoms flow through these channels when exposed to light. The inflowing ions cause the creation of an electrical signal which the nerve cell transmits to the brain.