I consider it a great honour to have been invited to give the William Carey Lecture, especially when one considers how much Carey contributed to the welfare of people in India. He was an outstanding man with many gifts and wide-ranging interests and influence -- in fields as diverse as botany, economics, medicine, print and communications technology, libraries, engineering, conservation, agriculture, social reform, astronomy and Indian religions. All his work was done in the name of God, and his Christian belief.

My address is entitled The Bionic Ear: Towards 2000 and beyond

I want to emphasise from the start that research directions beyond the year 2000 are built upon the achievements of the past and the present. Furthermore, although we have made great progress with the Bionic Ear, we have some distance to go before we can give most people near normal hearing.

To explain the basics of the normal hearing process: sound is transmitted down the ear canal, amplified by the middle ear, converted by the inner ear to electrical signals which are then transmitted as a code to the auditory centres of the brain for perception. Sound causes the ear-drum and bones in the middle ear to vibrate. These vibrations are transmitted to the inner ear where a membrane filters them into high and low frequencies. Hair cells on this membrane then move backwards and forwards and convert the vibrations to patterns of electrical pulses in the hearing nerve for transmission to the brain centres.

The Bionic Ear or Cochlear Implant is an electronic device that replaces the inner ear when it does not function. It has a microphone connected to a speech processor which sends radio signals to the implant in severely-to-profoundly deaf people, to by-pass the inner ear by electrically stimulating the hearing nerves with up to 22 wires. It thus helps very deaf people hear speech and other sounds.

What the Bionic Ear does for profoundly deaf people has been well described by an American cochlear implant patient, Beverly Biderman, in a new book called Turned On to be published later this year.

She says: 'Imagine yourself in a room with just a few close friends you love, talking and laughing. The conversation is quick and animated. It is too swift for you to follow on their lips, too difficult for you to understand because you are deaf. You sit in their midst with a frozen smile on your face, your cheeks aching, afraid to break the warm mood by telling them you are unable to understand. Your heart tightens and it aches. You feel angry that you are once again shut out; angry at yourself for being deaf, and at the world for expecting you not to be. Then, imagine another day, when you have a device implanted deep within your ear to help you to hear. Imagine that, with it, you can hear words and phrases in the air without looking for them on people's lips. You hear birds - not everything but enough to feel a part of the group. You hear birds that were once silent, music that was once noise. Your cheeks thaw. Your heart opens up. Your anger melts, and you feel a sense of grace.'

In the 1960s and 1970s most of the scientists and clinicians of the day said that a device such as the bionic ear was not possible in the foreseeable future, if at all. Their fundamental objections concerned such aspects as the complexity of the ear's functions and of speech-processing; possible damage to the ear in any operations upon it; and the probable lack of residual hearing nerves to work with.

The objections relating to the innervation of the inner ear and nerve die-back were answered by carrying out research to see how well electrical stimulation could reproduce the normal coding of sound frequencies in normal and deaf ears. According to one theory (place coding) the brain codes the frequency of a sound according to the place of stimulation within the inner ear and brain. The inner ear and the auditory pathways are arranged like a piano key board; you strike the bottom part and you get a low tone, strike the top and it sounds high.

Our research showed that electrical currents could be partly restricted to discrete groups of hearing nerve fibres for place coding, but some spread of current was almost inevitable.

The objection relating to damage to the inner ear was resolved by research which showed that electrodes could be safely inserted and stimulated without significant loss of the very nerves it was hoped to stimulate.

A further major objection, that speech was too complex to be understood via electrical stimulation, was resolved when I appreciated the importance of multiple-electrode rather than single-electrode...
stimulation so we could code speech frequencies on a place basis. This is the principle underlying our Bionic Ear.

However, I also realised that a speech processing system which aimed only at imperfectly reproducing the normal temporal and place coding of sound would not be satisfactory, because electrical stimulation created an electro-neural 'bottle-neck', limiting the flow of information from the external world to the nervous system. Hence, I saw the need to combine this with the presentation of the most important elements of speech.

However, to take the first step and develop a multiple-electrode system was a much more complex engineering task than producing a single-electrode implant. For this reason, I worked in collaboration with colleagues from the University of Melbourne's Department of Electrical Engineering to develop a totally implantable receiver-stimulator, or gold box, that would allow multiple-electrode stimulation.

It was also a much more expensive task, needing at least $200,000 per year. This level of fundraising was achieved through Sir Reginald Ansell's Channel 10 Telethons, and through Lions Club of Melbourne. It was then realised that sounds which produced excitation at the same location from Westinghouse Brakes came to me for electrical stimulation alone. This laboratory speech processor was, however, too big for our patient, Rod Saunders, to use in his daily life. Fortunately, at this time, an engineer from Westinghouse Brakes came to me to help.

Jim Patrick played a key role in the development of the University of Melbourne's prototype device, working on the electronic circuitry and the hermetically sealed gold implant box, with its equivalent of 6000 transistors on 10 silicon chips. The device also had two aerials: one for receiving data for the stimulus code and another for power to operate the device. This gold box was implanted by Brian Pyman and myself in our first patient, Rod Saunders, nearly 20 years ago on the 1st of August 1978 at the Royal Victorian Eye and Ear Hospital.

The first important finding on our patient, Rod Saunders, was that he could distinguish only the rate of stimulation up to a frequency of 300 pulses per second, which was consistent with our animal experimental results. Pitch ratios plateau at 300 pulses/second. This is much less than the 3000 cycles per second required for speech understanding.

The second important finding was that the sensations from individual electrodes could be scaled, not according to pitch, but according to timbre. Timbre is the quality of the sound and not the pitch per se. A violin and a piano may play the same note, but one may sound sharper or duller. Our patient could rank the electrodes from dull to sharp, according to the second formant which carries the most frequency area in the cochlea. But what elements of speech should we present to all the electrodes in the inner ear so that speech could be understood? To achieve this next goal we first developed a speech processor that operated like the normal inner ear and hearing nerve, and presented the output as electrical stimuli. Unfortunately this "physiological" speech processor did not work well because the stimuli had to be presented at the same time to different electrodes, and the electrical currents interacted with each other to produce unpredictable variations in loudness.

This finding, however, established an important principle in cochlear implant speech processing research: namely, that electrical currents should not be presented simultaneously to electrodes, and this principle was to guide all our further research endeavours. But we were forced back to square one to see how next to approach the problem.

The clue came when we appreciated that the patient was reporting vowel sounds rather than simple sounds when each electrode was stimulated. The vowels varied according to the electrode stimulated.

For a stimulus on an electrode in the high frequency area of the inner ear, the vowel /e/ as in "beat" was perceived; for a stimulus at the lower frequency or more apical part of the inner ear the vowel /ə/ as in "sort" was perceived. It was then realised that sounds which produced excitation at the same location in normal hearing people, were also perceived as similar vowels. These frequencies in speech are called formants.

The first and second formants for the syllables ba, da, ga are very important for speech intelligibility. Notice the feature that distinguishes these three syllables is the direction in movement of the second formant. As the second formant is the formant which carries the most intelligibility, we developed a speech processing strategy which extracted this second formant and used the current level to stimulate the electrode closest to that frequency area in the cochlea.

We also presented the other important component of speech, namely voicing as rate of stimulation. Voicing is important for telling whether the person is male or female, whether they have asked a question, and so on. Voicing is low in frequency and for this reason it was appropriately coded as rate of stimulation, as our previous studies showed that the discrimination of rate was only possible at the low frequencies required for voicing.

This strategy was implemented on our laboratory computer and enabled our patient to understand running speech when combined with lip-reading and also for electrical stimulation alone. This laboratory speech processor was, however, too big for our patient, Rod Saunders, to use in his daily life.
seeking a job. He was able to make the device as small as a binocular case. Wearing this device, Rod now had the confidence to make a purchase in a shop, a thing he was unable to do before the implant operation.

We could now enter an important new stage since funding became available through a Public Interest grant from the Australian Government for the research group to find an industrial partner, and also from the National Health and Medical Research Council to continue with the more fundamental research. The Australian pacemaker firm Teletronsics was selected as our industrial partner as the company had considerable expertise in bio-engineering.

Teletronics and its later holding company, Nucleus, implemented our speech processing strategy in a cochlear implant system that was smaller and more reliable than the one developed at the University of Melbourne. It was clinically trialled in a number of centres in North America and Europe for approval by the US Food and Drug Administration, and approved in 1985 as safe and effective for use in deaf adults who previously had hearing. It was the first multiple-channel device to be approved by the FDA or any other world health authority.

Meanwhile, we undertook further research to improve speech processing with the Bionic Ear. This research showed that we could add additional formants or the outputs from band pass filters on a place coding basis, and achieve improved speech perception scores. Improved results were obtained by progressively increasing the amount of information presented on a place coding basis, as well as the way the information is extracted from speech. The average scores have improved with each research advance, but although people now get very worthwhile hearing and can often converse on the telephone, we still have some distance to go before they can get the equivalent of normal hearing.

After establishing the benefits of the Bionic Ear in adults, we implanted the first three children in the world to receive this device at the Royal Victorian Eye and Ear Hospital in 1985 and 1986. This was the start of an international trial to also determine whether the Bionic Ear would benefit not only adults who had hearing before going deaf, but children who became deaf during their early life or who were born deaf.

The trial undertaken in Australia, North America and Europe, showed that 60% of children born deaf or deafened early in life, were able to understand some speech without lip-reading help and most of the remainder had significant help with lip-reading. The FDA approved the device as safe and effective for children two years of age and above in 1990, and it became the first cochlear implant of any type to be approved by the US Food and Drug Administration or any other world regulatory body for use in deaf children.

The implant thus became the first major advance in the management of profoundly deaf children not receiving satisfactory help with a hearing aid, since sign language was developed 200 years ago.

Before deciding to operate on children under two, it was necessary for us to undertake a series of biological studies to ensure that operating on a young child was safe. Young children of this age have special problems. These are, firstly, the effects of head growth, secondly, any complications from middle ear infection which they are prone to, and, thirdly, the effects of electrical stimulation on the developing nervous system. This research was part of a special five year contract to the US National Institute of Health, and I am pleased to report that all the studies did not shown any cause for concern for operations on young children.

However, although many children do very well with the Bionic Ear, when we analysed our results we found there is considerable variability in speech perception scores. The data also emphasises that the results are better the younger the child, and may be even better if the child is younger than two years of age.

To make further improvements in the Bionic Ear for children and adults, Cochlear Limited, in collaboration with the Co-operative Research Centre for Cochlear Implant Speech and Hearing Research, has developed a new implant system which is faster, smarter and smaller than the Nucleus 22 system and Mini implant which has been so effective and reliable. The new Nucleus 24 system is very thin so it can be implanted into very young children. Similarly, the size of the speech processor has been much reduced in the Nucleus 24 SPsrint wearable speech processor.

The Nucleus 24 System also has telemetry which can radio to the outside technician, the electrical activity in the inner ear and the responses of the auditory nerves to electrical stimuli. This will help us understand the biological changes in the inner ear after implantation, and also allow us to establish thresholds and comfortable levels for the device in children too young to tell us what they can hear.

Beyond 2000

In looking beyond the year 2000, research on sensori-neural deafness is needed in a number of areas.

The first area is to provide a better understanding of the way the brain codes sounds, and how this can best be reproduced by electrical stimulation with the Bionic Ear. Already our research is contributing answers to these questions. Each fibre in the brain cell carries some, but not all, of the timing information in response to the sound waves. It is the job of the brain cell to correctly identify the frequency relayed by the group of fibres, and it may do so by using a time window so that the cells only fire if a certain
number of the time intervals of the arriving responses are within that time window.

Our aim now with the Bionic Ear is to provide patterns of electrical stimuli in small groups of nerve fibres that are similar to those of sound. To achieve this fine temporal and spatial pattern of responses, a new electrode array will be required with many more electrodes to stimulate small groups of auditory nerve fibres.

The second challenge for the Third Millennium is to further improve the perception of speech and other sounds in noise. We are achieving further improvements in speech perception in noise using an adaptive beam-forming technique and two microphones.

A third important area of research beyond 2000 is to make the Bionic Ear invisible. Teenagers, for example, are very sensitive about their deafness, and although they may be getting good results do not always use their device in company. We have started research to develop a completely implantable Bionic Ear.

A fourth exciting area of research is in neurobiology, where we are studying the use of nerve growth factors to protect the hearing nerve from die-back after deafness. Not only could these nerve growth factors protect the hearing nerve from die-back but they could cause the hearing nerve to regenerate, something not thought possible ten years ago.

If we can also use other growth hormones to get the inner ear hair cells to grow again then we may be able to treat sensori-neural deafness with medical agents rather than surgery. The results of such neurobiological research could restore sensori-neural hearing in the next millennium.

The fifth exciting challenge for the third millennium is to better understand auditory plasticity and perceptual learning to help implanted children achieve optimal speech perception. It may even be possible in the next millennium to use nerve growth factors to facilitate a return of the plasticity required to develop the neural connections for the coding of the frequencies needed for speech perception. It may be possible to insert electrodes into the inner ear and have them slowly release growth factors which will pass along the nerve fibres and excite the gene responsible for making the factor and when it is released it will allow the appropriate reconnections of the nerves and brain cells.

In concluding, I would like to emphasise that in the third millennium a better understanding of how the brain codes sound, increased knowledge of the molecular biology of the brain, and advances in applying this knowledge to cochlear implants, hold out hope that most profoundly deaf people should be able to communicate near normally.

A third important area of research beyond 2000 is to make the Bionic Ear invisible. Teenagers, for example, are very sensitive about their deafness, and although they may be getting good results do not always use their device in company. We have started research to develop a completely implantable Bionic Ear.

A fourth exciting area of research is in neurobiology, where we are studying the use of nerve growth factors to protect the hearing nerve from die-back after deafness. Not only could these nerve growth factors protect the hearing nerve from die-back but they could cause the hearing nerve to regenerate, something not thought possible ten years ago.

If we can also use other growth hormones to get the inner ear hair cells to grow again then we may be able to treat sensori-neural deafness with medical agents rather than surgery. The results of such neurobiological research could restore sensori-neural hearing in the next millennium.

The fifth exciting challenge for the third millennium is to better understand auditory plasticity and perceptual learning to help implanted children achieve optimal speech perception. It may even be possible in the next millennium to use nerve growth factors to facilitate a return of the plasticity required to develop the neural connections for the coding of the frequencies needed for speech perception. It may be possible to insert electrodes into the inner ear and have them slowly release growth factors which will pass along the nerve fibres and excite the gene responsible for making the factor and when it is released it will allow the appropriate reconnections of the nerves and brain cells.

In concluding, I would like to emphasise that in the third millennium a better understanding of how the brain codes sound, increased knowledge of the molecular biology of the brain, and advances in applying this knowledge to cochlear implants, hold out hope that most profoundly deaf people should be able to communicate near normally.

Taralye is an early intervention centre that provides educational and support services within an integrated oral environment for hearing and hearing impaired children and their families. The kindergartens at Taralye form an important and integral part of the early intervention program.

The programs offered in the kindergarten rooms are designed to assist children (hearing and hearing impaired) in their acquisition of social, emotional, cognitive, language, physical, behavioural and general development skills.

Each kindergarten group has an experienced kindergarten teacher, kindergarten assistant, and teacher of the deaf, working with up to 4 hearing impaired children and 16-22 children with normal hearing. The teacher of the deaf works with the hearing impaired children, helping to develop language, social and independence skills as they participate in kindergarten activities.

The integrated program offered at Taralye provides a further extension to the experience of all the children. The interaction between hearing and hearing impaired children promotes the development of insight, tolerance and co-operative play skills.

The hearing impaired children wear amplification devices such as hearing aids, cochlear implants and radio frequency units appropriate to their hearing loss. The kindergarten teacher wears a transmitter with a head-level microphone.

The RF system allows the hearing impaired child to receive the best auditory input in a setting where there is background noise. By selecting an individual or group channel for the radio frequency aid, the teacher can speak to children as a group or individually.

The kindergarten rooms are especially designed to cut down on background noise when the kindergarten is in operation. Walls are carpeted with sound-absorbing materials and in one room there are a number of baffles to help reduce noise levels. Kindergarten teachers are also required to set up activities in the room in