Electrophysiological status indexed by early changes in impedance after cochlear implantation: A literature review

Lieber Po-Hung Li[a,b,c,d,*]

[a]Department of Otolaryngology, Cheng Hsin General Hospital, Taipei, Taiwan, ROC; [b]Faculty of Medicine, School of Medicine, National Yang-Ming Chiao-Tung University, Taipei, Taiwan, ROC; [c]Institute of Brain Science, School of Medicine, National Yang Ming Chiao Tung University, Taipei, Taiwan, ROC; [d]Department of Medical Research, China Medical University Hospital, China Medical University, Taichung, Taiwan, ROC

Abstract

Cochlear implantation is a major treatment option for severe-to-profound hearing loss. By insertion into the cochlea and stimulation of the cochlear nerve, cochlear implantation can improve the performance of hearing and speech performance of the implantees. The microenvironment of the cochlea is innate and gets disturbed in response to the insertion of a foreign body. However, real-time changes inside the cochlea in terms of electrophysiology at the molecular level can never be investigated in vivo in human beings. Thus, impedance is a good guide that reflects the electrophysiology inside the cochlea. Because the initial measurement of impedance cannot be performed earlier than the traditional interval of 1 month postoperatively, early changes in impedance have not been explored until recently; however, surgeons are now trying the initial switch-on earlier than 1 month after implantation. This review discusses the scenario of electrophysiological variation after early switch-on in <1 day postimplantation. Evidence has shown that fluctuations in impedance after implantation depend on the interplay between cell cover formation, fibrosis, electrode design, and electrical stimulation. Further studies addressing the correlation between impedance and clinical parameters are required to develop reliable biomarkers for better performance of cochlear implantation.

Keywords: Cochlear implantation; Electrode; Fibrosis; Impedance; Switch-on

1. INTRODUCTION

According to key facts about deafness and hearing loss, the World Health Organization proposed that "by 2050 nearly 2.5 billion people are projected to have some degree of hearing loss and at least 700 million will require hearing rehabilitation" (https://www.who.int/news-room/fact-sheets/detail/deafness-and-hearing-loss). Hearing technologies for rehabilitation include hearing aids, cochlear implants, and middle-ear implants. Cochlear implantation, among them, has been the major treatment option for severe-to-profound sensorineural hearing loss across all ages from children to the elderly. The prevalence of cochlear implantation is increasing due to factors such as financial support from governments worldwide. Surgical techniques and postoperative care for cochlear implantation have also been optimized in recent years that it can be a day-surgery with minimal invasiveness.

A cochlear implant comprises two main components: internal and external parts. The body of the internal part is embedded in the mastoid bone beneath the skin, and the electrode of the internal part is placed into the cochlea through the round window or cochleostomy during the surgery. The external part mainly comprises a speech processor, a coil, and a microphone. The speech processor and microphone are placed on the auricle of the outer ear, and the coil is positioned behind the ear just on the skin covering the body of the internal part. Communication between the two parts depends on the connection by the magnet inside the coil of the external part. The acoustic signals received by the microphone are processed into digital information by a speech processor and then transmitted through the coil to the electrode. When the cochlear nerve is stimulated by digital information from the electrode, acoustic signals are transferred to the brain, and implanted patients are able to hear again. By inserting the electrode into the cochlea and stimulating the cochlear nerve, cochlear implantation can improve the hearing, speech, and music performance of the hearing-impaired.[1,2]

The microenvironment of the cochlea is an innate system in nature, and logically, it is disturbed to some extent in response to the insertion of an electrode as a foreign body. These disturbances in the microenvironment due to the insertion certainly have some effect on the performance of the device. It is an interplay between the implant and the circumstances surrounding the electrodes. However, real-time changes inside the cochlea after implantation in terms of electrophysiology at the molecular level can never be explored in vivo in human beings.

Among other tools, the impedance of the electrode is a good and important guide for reflecting the electrophysiological

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* Address correspondence. Dr. Lieber Po-Hung Li, Department of Otolaryngology, Cheng Hsin General Hospital, 45, Cheng Hsin Street, Taipei 112, Taiwan, ROC. E-mail address: phli@gm.ym.edu.tw (L. P.-H. Li).

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variations inside the cochlea. Because details about the performance of the electrode, magnitude of current flow, and energy demand of the device can be indexed by the detection of impedance,[3] field telemetry of impedance has thus become one of the most popular methods of measurements easily accessible for cochlear implantation. Therefore, by observing the variation in impedance, information about intracochlear changes in the surrounding encompassing electrodes can be predicted.[3–6] Impedance is also a useful tool for the optimization of most comfortable levels in terms of stimulus and settings for the cochlear implant.[7] In addition, impedance can be a potential biomarker highly correlated with imbalance disorder[6] and/or performance of hearing as well speech after the surgery.[8–11]

The first contact between the two main components of a cochlear implant after surgery is called the initial switch-on.[12] Subsequently, it is followed by a series of frequency mapping to optimize the performance of a cochlear implant for the commencement of a training program for hearing and speech. Traditionally, initial frequency mapping and training programs can only begin no sooner than 3 weeks postoperatively, regardless of the various surgical approaches currently utilized for cochlear implantation.[13,14] Although surgical techniques have been optimized, the initial switch-on cannot be performed earlier than the traditional interval of approximately 1 month postoperatively. Early changes in impedance immediately after insertion were unexplored until recently; however, surgeons worldwide are now trying the initial switch-on earlier than 1 month after implantation.

Experiences about initial switch-on within 24 hours following cochlear implantation have been reported in studies from different countries.[8,9,12,15–19] Some of these studies reported that the key issue, among others, for the success of first mapping in <1 day is dedicated at least in part to factors including surgical procedures and wound managements.[12,15–18] Details of these factors included but were not limited to microinvasive technique, decreased edema without injury in the peri-incision region, and adverse events to the perilymph following insertion of electrodes.[12,15–18] Issues about safety and practicability of earliest switch-on in <1 day postoperatively have been reported previously[20]; however, serial changes that occur after implantation inside the cochlear using electrophysiology have never been reviewed.

This review discusses the scenario of electrophysiological variation in terms of early switch-on in <1 day postimplantation. Currently, there are three major manufacturers of cochlear implants, and the scenario of changes in the impedance for each manufacturer is different. Arguments on these differences were addressed. We aimed to elucidate the clinical impact of this procedure on implantees.

2. SCENARIO OF CHANGES IN ELECTROPHYSIOLOGICAL PARAMETERS AFTER EARLIEST INITIAL SWITCH-ON WITHIN 24 HOURS OF COCHLEAR IMPLANTATION

Electrically evoked compound action potential (ECAP) remains relatively stable as long as up to 5 to 6 years postimplantation.[21] On the contrary, variation in both impedance and ECAP is generally observed days or weeks after the implantation.[22,23] These changes are due to factors including cascades of responses to a "foreign body"-like effect resulting from the insertion of electrodes into the inner ear.[24,25] Such effects were unclear on the electrophysiological events minutes to hours after the implantation until 2013, when results of earliest initial mapping in <1 day postimplantation were reported for the first time.[12] There are indeed differences between electrodes from various manufacturers with respect to scenario of changes in electrophysiological parameters after earliest initial switch-on within 24 hours of cochlear implantation.

3. DEVICES BY COCHLEAR (COCHLEAR™, LANE COVE, NSW, AUSTRALIA)

3.1. Drop in impedance 24 hours after the surgery in comparison to intraoperative monitoring

Electrical levels measured after the insertion of an implant into the cochlea of animals tend to drop within days.[26] Owing to factors described in the earlier sections about the dilemma of initial switch-on earlier than the traditional scenario of 3 to 4 weeks after cochlear implantation, relevant issues can only be explored in animal models for an extended period in the past. However, an immediate decrease in impedance/ECAP in human beings has been reported within 24 hours after cochlear implantation in comparison to those detected during surgery.[12] This phenomenon was later verified in another study from the same group[16] and by another team using a different electrode from the same manufacturer.[19]

Why do impedance and ECAP significantly drop in <1 day postoperatively? Owing to the innate nature of the cochlear system, electrophysiological fluctuation following the surgery must theoretically be related to the reorganization of the milieus around the electrode array on site.[27] One possibility could be associated with ups and downs of events provoked by responses to foreign body due to insertion of the implant into the cochlea.[28,29] Air bubbles produced due to the implantation, although vaporized soon later, certainly contribute to a surge in impedance intraoperatively.[30] Fibers of spiral ganglion could also become swollen shortly after the implantation but recover soon following the invasive effect.[31] These responses would trigger the surge in impediment and a quick return for the sensitivity of ganglion neuron, respectively.[26] It has also been shown that a sheath-like matrix should have formed surrounding the intracochlear part of the implant immediately after the insertion, which in turn could lead to the rise of the impedance and thus ECAP for contacts of each electrode.[4,12,24,32] This matrix of cell cover might comprise materials such as protein adsorption, and immune cells such as macrophages as well as fibroblasts.[4] The continuity of these tissue envelope would possibly be disorganized or even damaged due to spurt of cells through transmission of electrical stimulus after initial activation of the device, a divergence effect called "blow-out" in previous studies.[4,33,34] Therefore, impedance and ECAP are predicted to be reduced, because logically the integrity of the tissue matrix should be in direct proportion to the magnitude of impedance.[33,35] What added to the reduction in impedance would be a hydride layer made after the above events of cell escape, because the layer has been shown to be able to enlarge the area of contact along the array of electrodes.[36]

It is noteworthy that in the intraoperative monitoring, the values of impedance decreased in an apical-to-basal direction along the cochlea.[12] This phenomenon was in line with earlier researches and was again verified later.[16,37,38] The underlying mechanism might be associated with the size of electrode array because impedance is inversely proportional to the geometric area of the contact surface.[3] Because the contact area increases all the way from apical to the basal array, the basal segment of electrodes would reasonably have the lowest values of impedance, at least for the Nucleus 24RECA implant system.[16]

3.2. Between 24 hours and 4 weeks

What follows the drop in 24 hours is an obvious increase in impedance during the first 4 weeks after surgery.[16] It is interesting that the behaviors of the trend for segments differed in impedance measurements. A previous study revealed that there is a smooth increase in basal as well as midportion arrays and a minor decrease in the apical array.[16] For the apical array, the impedance first increased to the highest level at 1 week before decreasing afterward.[16] This could be a special route of evolution exclusive to the earliest switch-on. In some previous studies, evidence had it that the trend of impedance increased within 2 weeks before the initial activation.[37,38] In contrast, the impedance values continued to increase from day 1 to 4 weeks after the initial activation for the basal and middle part of the array.[16]

In addition to the aforementioned events of cell cover and electrical stimulation, fibrosis induced at a later stage also contributed to the end results of the interplay for impedance measurement during this period. Evidences showed that cell cover and fibrosis both lead to increase in impedance, and launched within hours and days postoperatively, respectively.[10,27,34,39,40] Effect of electrical stimulation has been revealed to be more obvious on the surface of contact (ie, cell cover) than on the matrix around the electrode (ie, fibrosis), possibly due to structural differences between them.[3] Estimates proposed that electrical stimulation could contribute to around 20% decrease in impedance from 2 to 10 weeks, while only around 5% decrease from 1.5 to 5 years postoperatively.[3,4,39] Therefore, previous studies showed that cell cover played a much more important role with respect to impedance measurement within the first few weeks after cochlear implantation,[3] because it is logical to conjecture that fibrosis is more resistant to electrical stimulation compared with cell cover.[10,16] In addition, the basal part of the electrodes has more fibrosis in comparison to the apical part after cochlear implantation.[37,41–43] This finding anatomically corresponds to the lateral wall for the basal turn of the cochlea, the area most easily injured on insertion,[34,43,44] which in turn could justify the increase in impedance of basal segment during this period. The impedance between 4 and 8 weeks as well as thereafter was stable with little interval differences,[16,27,30,34,45] possibly indicating an ultimate equilibrium among factors including cell cover, electrical stimulation, and fibrosis.[46]

4. DEVICES BY ADVANCED BIONICS (ADVANCED BIONICS™, STÄFA, SWITZERLAND)

Contrary to the above findings, impedance was later observed to be increasing instead of decreasing 1 day after cochlear implantation for the implant system manufactured by a different company (HiFocus 1J; Advanced Bionics™) for the first time.[17] The scenario for the postoperative changes in impedance for various devices (ie, Mid-Scala and Nucleus 24RECA) were also observed to be different.[7] Although the results were incongruent with earlier research in animal model, where the reduction in the level of electrical detection persisted days after electrode insertion,[26] these studies again verified factors leading to changes in impedance measurements including sheath formation, size of the electrode, fibrosis formation, and electrical stimulation.[7,17]

However, the mechanisms underlying these differences remain unclear. One possible explanation is the surgical approach. The implant was inserted through the round window in the Advanced Bionics™ researches[7,17] and cochleostomy in the aforementioned Cochlear™ study.[16] According to the animal model, there might be an effect on the cochlea using different techniques, with less tissue formation through the round window approach.[47] Another reasonable explanation could be the methodology of monitoring. The timing of impedance measurement for the Advanced Bionics™ device was in the beginning, while for the Cochlear™ device, it was measured at the end of the cathodic phase for the biphasic cathodic-anodic pulse, representing "access resistance" and total impedance (ie, sum of access resistance and polarization impedance), respectively.[7] This could also be a major factor because access resistance usually increased in a relative smooth way while polarization impedance went down sloping after switch-on.[3]

There are differences in the device design in terms of electricity. According to Ohm's law, electrical power is directly proportional to electrical resistance and square of electrical current.[17] Basically the electrical current was relatively equal between Advanced Bionics™ and Cochlear™ devices.[17] However, electrical resistance was much higher in Cochlear™ than in Advanced Bionics™ implants, with a maximum of approximately five times of the value.[17] This in turn could lead to a much bigger pulse of electrical power passing by way of electrodes to the cell cover and fibrosis surrounding the Cochlear™ devices and therefore a greater effect of "blow-out" than in the Advanced Bionics™ devices.[17] The authors also argued about the possibility of sheath formation effect,[4,48] which might result from increased quantity of cell cover and fibrosis formation due to different positions inside the cochlear space for devices from different manufacturers.[49,50] Although this effect could lead to an increased level of impedance, it remains to be investigated.

For the intraoperative measurements, values of impedance telemetry were increased in the basal-to-apical direction of the cochlea,[7] which was in line with a previous study that used device from another manufacturer.[16] For the Advanced Bionics™ device, the contact size was also decreased in the basal-to-apical direction,[7] and same was observed in Cochlear™ device.[16] Thus, this tendency can be expected from the trend of contact size, because impedance is inversely proportional to the contact area of electrodes.[3] The scenario of impedance from 1 day to 2 months was relatively smooth without significant changes.[7,17]

5. DEVICES BY MED-EL (MED-EL™, INNSBRUCK, TYROL, AUSTRIA)

The impedances of the Med-El™ device were revealed to be significantly decreased when measured intraoperatively in comparison to those measured 1 day later.[8,9,51] The trend was compatible with that noted in devices of Advanced Bionics™[7,17] and different from that of Cochlear™ devices.[12,15,16] There was no significant change even after 1 year postoperatively.[9]

On the contrary, the impedances of the Med-El™ device were revealed to be significantly increased when measured intraoperatively in comparison to those measured in the recovery room on the same day under conscious sedation (CS).[8] The authors ascribed the reasons to be air bubbles or inflammatory process.[8] There was no significant change from 2 to 8 weeks postoperatively.[8] However, the limit of the study resided in the fact that the sample size was small (ie, nine implantees in total).[8] Further studies are necessary to clarify the scenario of impedance change after early switch-on under CS.

In conclusion, hearing loss is a major disease with social burden that is progressively increasing in recent years. Overthe past few decades, cochlear implantation has become a well-developed option for the optimal rehabilitation of patients with severe-to-profound hearing impairment. As a foreign body, the inserted implant certainly has some effect on the innate circumstances of electrophysiology inside the cochlea. Because the real conditions at the molecular level can never be explored in vivo with respect to human beings, impedance should be a good indicator for monitoring changes in the microenvironment of the cochlea. Although findings from animal models suggest that electrophysiological parameters begin to fluctuate soon after insertion, early changes in impedance after cochlear implantation in human beings remain unclear because traditionally the initial measurement can only be made approximately 1 month after surgery. The experiences of earliest initial switch-on from various teams worldwide can now be found in the relevant literature database. Evidence has revealed that the final results of the measured values for impedance depend on the equilibrium among parameters including cell cover formation, growth of fibrosis, electrode design, and electrical stimulation. Further studies are needed to address the association between impedance values and parameters of clinical entities, which in turn could promise the development of a reliable biomarker for a better performance of cochlear implantation.

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