The Laryngoscope

The Impact of Repetitive Hyperbaric Exposure during SCUBA Diving on Cochlear Implants

Justin M. Hintze, MD; Lina Geyer, MD; Conall W. Fitzgerald, MD; Cristina Simoes Franklin, PhD; Fergal Glynn, MD; Laura Viani, MD; Peter Walshe, MD

Objectives/Hypothesis: Complications during or after cochlear implantation are relatively rare. They occur more frequently in patients who partake in activities that can potentially lead to local trauma. No formal recommendations exist for participation in self-contained underwater breathing apparatus (SCUBA) activities. We describe three patients with a combined five cochlear implants and extensive diving experience, the largest case series to date, and highlight some of the difficulties faced. We also review the literature on previously described SCUBA-diving patients with cochlear implants.

Study Design: Retrospective case series and literature review.

Methods: A review of the known SCUBA divers in the National Hearing Implant and Research Centre in Ireland was conducted, and a review of the literature was carried out using PubMed and Google Scholar.

Results: Of the three SCUBA divers with cochlear implants, two required reimplantation, the first due to nonauditory stimulation, and the second due to extrusion of the electrode through the tympanic membrane following repetitive SCUBA dives. The third patient remains without complications after 80 dives.

Conclusions: Patients with cochlear implants can have complications relating to the implant itself, with device failure a theoretical risk. The cochleostomy can lead to perilymphatic extravasation, as well as inner ear barotrauma, decompression sickness, and formation of air bubbles along the electrode. A combination of deafness, vestibulopathy with abrupt perilymph leak, and loss of proprioception can lead to disorientation and blue dome syndrome. Based on our experience with cochlear implants in SCUBA divers, along with those reported in the literature, we recommend caution in patients with cochlear implants who SCUBA dive regularly and strict adherence to the recommended safety limits.

Key Words: Cochlear implant, self-contained underwater breathing apparatus, diving.

Level of Evidence: 4

***Laryngoscope*, 9999:1–5, 2019**

INTRODUCTION

Since the initial development of cochlear implants, there have been significant changes in both technological development and surgical techniques. Although device complications during or after cochlear implantation are relatively rare and are reported as occurring in 2% to 4% of cases, they do occur more frequently in children and in adult patients who partake in activities that can potentially lead to local trauma.[1] In some cases where there is device failure or severe complications, surgical revision or explantation is required.

Patients with cochlear implants are usually advised to avoid contact sports, as the potential external forces can disrupt the implant. For water sports, only the external speech processor should be removed. Some manufacturers supply waterproof pouches so that the external components can be worn while swimming. During diving, several changes occur within the middle ear; the tympanic membrane deflects inward during descent, due to reduction in the volume of the middle ear gas; a descent of 10 meters causes a 50% reduction in volume, as described by the Boyle-Mariotte law, which is explained later. Failure to equalize middle ear pressure via the eustachian tube can lead to pain, perforation of the tympanic membrane, and even excess pressure of the stapes footplate on the oval window leading to round window perforation and perilymphatic egress. During ascent, the tympanic membrane bulges outward due to volume expansion in the middle ear. Problems relating to this are less frequently observed, as airflow out of the eustachian tube is less obstructed by escaping air. However, excessive pressure within the middle ear also has the potential to rupture the round window membrane and lead to inner ear decompression sickness caused by perilymphatic leakage.[2]

Although cochlear implant manufacturers have their own recommended diving limits, no formal recommendations exist for participation in self-contained underwater breathing apparatus (SCUBA) activities. Implants manufactured by Cochlear are validated to withstand pressures up to a depth of 40 meters (CI500, CI24RE) and 25 meters

From the National Hearing Implant and Research Centre (J.M.H., L.G., C.W.F., C.S.F., F.G., L.V., P.W.) and Department of Otolaryngology–Head and Neck Surgery (J.M.H., L.G., C.W.F., F.G., L.V., P.W.), Beaumont Hospital, Dublin, Ireland; the Royal College of Surgeons in Ireland (J.M.H., C.W.F., L.V., P.W.), Dublin, Ireland; and the School of Medicine (C.S.F., L.V.), University of Dublin, Trinity College, Dublin, Ireland.

Editor's Note: This Manuscript was accepted for publication on January 29, 2019.

This Manuscript was received on November 7, 2018, revised on December 27, 2018, and accepted for publication on January 29, 2019.

The authors have no funding, financial relationships, or conflicts of interest to disclose.

Send correspondence to Justin M. Hintze, MD, Department of Otolaryngology–Head and Neck Surgery, Beaumont Hospital, P.O. Box 1297, Beaumont Road, Dublin 9, Ireland. E-mail: hintzej@tcd.ie

DOI: 10.1002/lary.27880

(CI24R, CI24M, CI22M), whereas Advanced Bionic devices have been tested up to a depth of 42 meters (HiRes Ultra) and 10 meters (HiRes 90k) in an AquaCase cover (Table I).[3,4] Although these depths have been established ex vivo, very little data exist with regard to in vivo experience with cochlear implants and are limited to only case reports.

With that in mind, we describe three patients with a combined five cochlear implants and extensive diving experience, the largest case series to date, and highlight some of the difficulties and challenges faced. We also review the literature on previously described SCUBA diving patients with cochlear implants to help formulate recommendations for this cohort of patients.

MATERIALS AND METHODS

A review of the known SCUBA divers in the National Hearing Implant and Research Centre in Ireland was conducted. Chart reviews, patient interviews, and detailed analyses of the divers' personal and complete diving logs via dive computers was carried out.

A review of the literature was carried out using PubMed and Google Scholar between 2018 and 2000 using the following search strategy: (cochlear AND implant) AND (diving OR scuba). Only articles available in English or German were included. Four articles were retrieved and screened. Three articles were available for final review. Only two articles described experience with cochlear implants in SCUBA diving patients, and one article described ex vivo data.

RESULTS

All patients underwent cochlear implantation at the National Hearing and Implant Centre. A retroauricular incision was made, and a periosteal flap raised for processor placement. A mastoidectomy was used to access the middle ear, and the facial recess was opened. The round window was identified, and the electrode inserted through the round window membrane. A fibrin sealant was then used to cover the round window and fill the mastoid, covered by an absorbable gelatin sponge, and the processor placed below the periosteum.

The first patient, a 40-year-old male at the time of first implantation, with hereditary bilateral profound hearing loss (90–100 dB reduction across all frequencies) underwent cochlear implantation with a Cochlear CI24RE(ST) on the right side. He had extensive diving experience prior to implantation as a recreational diver and SCUBA diving instructor. Preoperative magnetic resonance imaging (MRI) showed no abnormalities, and his perioperative and postoperative course was uneventful. A postoperative skull x-ray showed the implant to be in a good position. The patient continued to perform regular nondecompression dives, at an average depth of 25 meters and a maximum depth of 41 meters (Table II). He recommenced his diving activities 3 months after surgery. Four years later he started developing pain along his upper jaw and otalgia, symptoms in keeping with nonauditory stimulation (NAS). At this stage, he had performed in excess of 400 dives with the implant. The patient temporally linked these changes in his symptoms to an episode while diving, whereby an unexpected underwater swell caused a rapid ascent from 36 meters. His symptoms necessitated the switching off of the nine most basal electrodes, followed by a further deactivation of four additional electrodes 1 year later (E1–E13). Impedance testing demonstrated a slight increase in impedance of the affected electrodes of up to 10.0 to 11.0 kΩ. These results, however, are still well within the good range, as specified by the manufacturer. Subsequent computed tomography (CT) of his temporal bones demonstrated the cochlear implant to still be in a good position, with no other abnormalities detected. After a multidisciplinary discussion, a decision was made to explant and reimplant a new cochlear implant. Revision surgery was performed, where his old cochlear implant was exchanged for a new Cochlear CI512. Direct analysis of the returned device, performed by the manufacturer, did not demonstrate any faults in the device, including basic functional tests, visual inspection, insulation tests, and direct current testing. His postoperative course was uneventful, and at most recent review 2 years after his second implant, he is doing well. With the second implant, he has performed 40 dives up to a depth of 40 meters, with an average depth of between 20 to 25 meters.

The second patient, a 28-year-old female with congenital profound hearing loss, underwent cochlear implantation with a Cochlear CI24RE(CA). Her preoperative MRI showed a normal-appearing cochlea and nerve. Her postoperative course was largely uneventful, aside from some mild dizziness, and a skull x-ray confirmed the implant to be in a good position. She continued to be followed regularly according to the National Hearing Implant and Research Centre protocol, and was advised to only start diving again 3 months after her surgery. Four years after implantation she started to complain of otalgia and otorrhea. She was experiencing intermittent bouts of sharp pain, lasting seconds and occurring sporadically. At this stage she had completed 30 nondecompression dives at an average depth of 20 meters and a maximum depth of 42 meters. Otoscopic inspection revealed the implant electrode had migrated out of the tympanic membrane (Fig. 1), with retraction of the tympanic membrane onto the round window. Keratin was seen tracking into the facial recess. She was not able to make a definite temporal link, but did attest to several dives performed up to and beyond the manufacturers limit of 40 meters and to performing dives with rapid descent and ascent. After extensive discussion with the patient and the multidisciplinary

TABLE I.
Cochlear Implant Devices and Recommended Maximum Depth.

Manufacturer	Device	Maximum Depth (m)	Source	Reference No.
Cochlear	CI500	40	Manufacturer data	3
	CI24RE	40	Manufacturer data	3
	CI24R	25	Manufacturer data	3
	CI24M	25	Manufacturer data	3
	CI22M	25	Manufacturer data	3
Advanced Bionic	HiRes Ultra	42	Manufacturer data	4
	HiRes 90 k	10	Manufacturer data	4
MED-EL	MED-EL Combi40	43	Case report	10
	MED-EL Combi40+	43	Case report	10

TABLE II.
Reported Cases of Cochlear Implants in SCUBA Divers.

Reference	Age, yr/Gender	Device	Dives	Maximum Depth (m)	Average Depth (m)	Complications
Present study, 2018	40/M	Cochlear CI24RE(ST)	420	41	25	NAS, explant
Present study, 2018	47/M	Cochlear CI512	40	41	20–25	None
Present study, 2018	28/F	Cochlear CI24RE(CA)	30	42	20	Electrode extrusion through the TM, explant
Present study, 2018	32/F	Cochlear CI24RE(CA)	10	20	15	None
Present study, 2018	44/M	Cochlear CI24RE(CA)	80	40	15–20	None
Zeitler et al. 2018	NA	NA	20	28	NA	None
Kompis et al. 2003	51/M	MED-EL Combi40	89	43	15.1	None
Kompis et al. 2003	51/M	MED-EL Cobmi40+	68	43	15.0	Short circuit between the two most apical electrodes

F = female; M = male; NA = not available; NAS = Nonauditory stimulation; SCUBA = self-contained underwater breathing apparatus; TM = tympanic membrane.

team, the patient opted to have the implant replaced. She underwent replacement of her cochlear implant with a Cochlear CI24RE (CA) and cartilage tympanoplasty. Postoperatively she has made a good recovery, and at her most recent follow-up, her tympanic membrane and cochlear implant remain intact. She has performed 10 dives with her new cochlear implant, but has significantly reduced her diving as well as depth of dives.

The third patient, a 44-year-old male at the time of implantation, underwent cochlear implantation using a Cochlear CI24RE(CA). He has bilateral congenital hearing loss, his preoperative MRI showed normal inner ear anatomy, and his peri- and postoperative course was uneventful. Since implantation he has performed 80 non-decompression dives up to a depth of 40 meters at an average depth between 15 and 20 meters. He has not experienced any complications relating to his cochlear implant to date, 4 years after implantation.

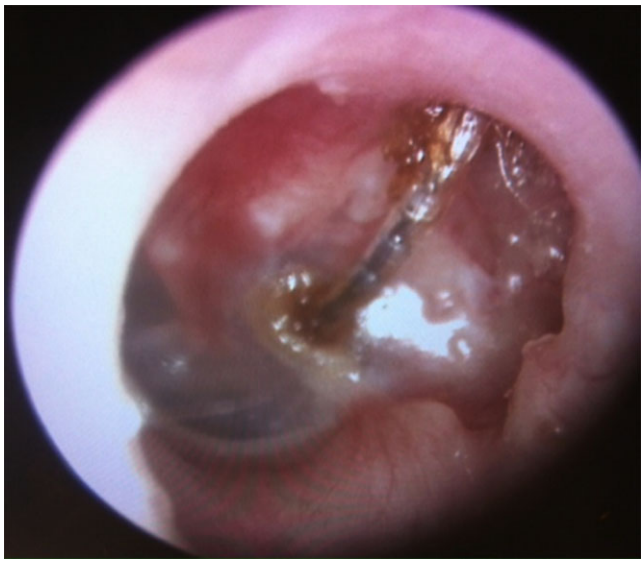

Fig. 1. Otoscopic inspection revealing migration of the implant out of the tympanic membrane. [Color figure can be viewed in the online issue, which is available at www.laryngoscope.com.]

DISCUSSION

Most recreational SCUBA divers are subjected to pressures between 1 to 5 atmospheres absolute (ata) during dives up to depths of 40 meters. According to the Boyle-Mariotte law, which states that at equal temperature the volume and pressure of a gas are constant, a 10-meter (2 ata) descent causes a reduction in gas volume by 50%. A further 50% reduction occurs when descending from 10 to 30 meters (4 ata). These volume changes can have significant effects on all gas-containing objects in the body, including lungs, middle ear, sinuses, and even the air within the implant. Tympanic membrane perforations can occur due to inadequate equalization during descent, or preexisting conditions, including eustachian tube dysfunction, leading to the entrance of fluid into the middle ear. Otolaryngological problems are among the most common issues encountered by divers, with up to 80% of divers reporting some form of ear, nose, and throat complaint relating to diving.[5,6] There are a multitude of otolaryngological considerations and problems that can occur when diving, which are outlined at length by Klingmann et al.[7] and Lechner et al.[2,8] The most common otolaryngological problem to occur during diving is compression barotrauma of the middle ear. During the first 10 meters, the middle ear volume reduces by 50%, causing the tympanic membrane to deflect inward. The prevent this, the negative pressure needs to be equalized via the eustachian tube. Failure to do so (either due to inability to open the eustachian tube or too rapid descent) causes the tympanic membrane to bow into the middle ear, leading to pain and ultimately perforation.[2] Various otolaryngological guidelines exist for giving divers recommendations with respect to their fitness to dive. The UK Diving Medical Committee (UKDMC), Professional Association of Diving Instructors (PADI), and the South Pacific Underwater Medicine Society (SPUMS) advise on recommendations for recreational diving, whereas the Health and Safety Executive, the Association of Diving Contractors International, and the European Diving Technology Committee (EDTC) advise on commercial diving. The UKDMC and PADI recommend a questionnaire, followed by a medical examination for any positive answers, whereas the SPUMS requires a mandatory examination by an accredited doctor.[8] None of these

make any comments on cochlear implants,[8] and there is a paucity of evidence with respect to recommendations for cochlear implant patients and diving. Only three case reports exist on this subject,[9–11] and there are no official recommendations. Although both Cochlear and Advanced Bionic have been tested and are validated to withstand pressures between 2 and 5 ata (10–40 meters) depending on the implant,[3,4] these data have not been established in vivo.

Patients with cochlear implants can have complications relating to the implant itself, with implosion and device failure a theoretical risk at elevated pressures due to the air contained within the implant. Furthermore, the cochleostomy created during implantation of the cochlear implant can potentially lead to perilymphatic fistulation due to negative pressures within the middle ear experienced during descent (this causes the tympanic membrane to bulge inward, leading to the stapes footplate being pushed into the oval window and potentially rupturing the round window), leading to perilymphatic extravasation, as well as inner ear barotrauma and formation of air bubbles along the implant electrode. The less commonly experienced decompression barotrauma on ascent is also more likely to be experienced by divers with cochlear implants. This reserve squeeze occurs due to air expansion during ascent, causing the tympanic membrane to bulge out and potentially lead to rupture of the round window due to excessive middle ear pressure. This can occur more easily if the round window membrane has been artificially pierced, as occurs during cochlear implant insertion.[3,4] There is, therefore, a theoretical risk of inner ear decompression sickness. The perilymphatic fistulation and extravasation may also lead to the cochlear implant electrode being pushed out of the cochlea.

Another consideration for patients with CIs with respect to diving is that their inner and middle and inner ear anatomy may be altered, and may expose them to increased risks of diving-related complications. Patients also need to be instructed to remove the external component, leaving them deaf for the duration of the dive. With regard to mastoid surgery, few formal recommendations exist. PADI lists a history of mastoidectomy as a relative risk; however, the UKDMC and SPUMS make no recommendations. The EDTC allows for diving after simple mastoidectomy, but not following atticotomy.[8] There is a paucity of evidence of recommendations regarding mastoid surgery and diving, but a theoretical risk of egression of air into soft tissue and around the implant processor site can occur, resulting in emphysema and processor dislodgement.

A combination of deafness, vestibulopathy with abrupt perilymph leak, and loss of proprioception during diving can lead to disorientation. This can be exacerbated by night diving, where peripheral vision is limited with torchlight. Blue dome syndrome, a combination of the above, and an inability to see the seabed and surface is a recognized entity already.

The first report of a patient using a cochlear implant while diving was by Kompis et al. in 2003 (Table II).[10] They reported on a patient with bilateral cochlear implants (MED-EL Combi40 and MED-EL Combi40+). The patient completed a total of 89 dives at a maximum depth of 43 meters with the former, and 68 dives up to 43 meters with the latter implant. Although subjectively perceived benefit and speech recognition scores remained stable, the second implant (MED-EL Combi40+) was found to have developed a short circuit between the two most apical electrodes. The first implant remained functional.[10] Zeitler et al., in 2018, reported on a patient with a unilateral cochlear implant that underwent 20 SCUBA dives up to a depth of 28 meters. Audiometric testing and internal receiver stimulation of the cochlear implant showed no changes before and after SCUBA diving.[11]

In our series of three patients with five cochlear implants, two required explantation, one due to NAS and one due to migration of the electrode through the tympanic membrane causing perforation and retraction. All patients remained within 2 meters of the manufacturer recommended limits of depth. The surgical approach used with all patients involved insertion of the electrode through the round window membrane, which was then covered with fibrin sealant. A potential future surgical consideration for patients willing to SCUBA dive with cochlear implants is the use of a round window sealant, such as temporalis fascia, to help reduce the risk of electrode migration out of the round window, and also helping to support the round window against compression and decompression trauma. Although it is impossible to accurately determine the exact moment of implant failure, both patients in our series reported issues arising due to unforeseen circumstances, underwater swells, or rapid descent and ascent at depths well below the recommended depth limit. It is thus reasonable to assume that these problems arose not during a single dive, but due to repeated hyperbaric exposure. The second patient may have had eustachian tube dysfunction, leading to an inability to properly equalize middle ear pressure, causing retraction of the tympanic membrane over the implant electrode over time, whereas the first patient may have experienced an element of perilymphatic fistulation and extravasation leading to migration of the electrode out of the cochlea during the episode of sudden ascent. Of the patients reported in the literature, one out of the three cochlear implants experienced a short circuit of the two most apical electrodes; however, the patient did not report any subjective deterioration. This means that of the eight cochlear implants in divers reported in the literature, two required explantation, and one experienced a fault. This is a 25% failure rate, and a 13% fault rate. In our series, the largest reported to date, we report a 40% explantation rate of cochlear implants in patients who continued to SCUBA dive.

With SCUBA diving becoming more popular and cochlear implants becoming more prevalent, more of these problems may be seen in the future. The fact that the greatest air volume change in the middle ear occurs in the first 10 meters of descent and ascent means that the likelihood of problems in recreational scuba diving may be similar to dives of greater depth. This has significant morbidity and financial implications, as repeated cochlear implant surgery is not without risks, along with the financial costs associated with cochlear implants.

CONCLUSION

Based on our experience with cochlear implants in SCUBA divers, along with those reported in the literature

(Table II), we recommend significant caution in patients with cochlear implants who SCUBA dive regularly, along with diligent recording of dives with a dive computer. Patients should also be strictly adherent to current guidelines for diving with otolaryngological conditions, as outline by commercial and recreational diving organizations.[8] It is impossible to know at this stage what the risk factors for cochlear implant failure in SCUBA divers are, and should be investigated in future larger-scale studies. Furthermore, whereas cochlear implants themselves have been certified to certain depths, including up to 40 meters, it should be noted that there is currently no case series reported on reliable effects of pressure changes in cochlear implants in vivo. Further in vivo research needs to be conducted before better advice for use of cochlear implants in divers can be given. We would also recommend for recreational diving organizations to include these recommendations in their future guidelines.

BIBLIOGRAPHY

1. Battmer RD, O'Donoghue GM, Lenarz T. A multicenter study of device failure in European cochlear implant centers. *Ear Hear* 2007;28(2 suppl):95S–99S.
2. Lechner M, Sutton L, Fishman JM, et al. Otorhinolaryngology and diving-part 1: otorhinolaryngological hazards related to compressed gas scuba diving: a review. *JAMA Otolaryngol Head Neck Surg* 2018;144: 252–258.
3. Cochlear. Safety information for cochlear implant recipients and their carers. British Cochlear Implant Group website. Available at: https://www.bcig.org.uk/wp-content/uploads/2018/01/Cochlear.pdf. Accessed December 23, 2018.
4. Advanced Bionics. Safety information for cochlear implant recipients and their carers. British Cochlear Implant Group website. Available at: https://www.bcig.org.uk/wp-content/uploads/2018/01/Advanced-Bionics.pdf. Accessed December 23, 2018.
5. Strutz J. Otorhinolaryngologic aspects of diving sports [in German]. *HNO* 1993;41:401–411.
6. Vandenhoven G, Collard F, Schamp E. Children and diving: medical aspects. Eight years' sports medical follow-up of the first scuba diving club for children in Belgium. *SPUMS J* 2003;33:70–73.
7. Klingmann C, Praetorius M, Böhm F, Tetzlaff K, Plinkert P. T Fitness to dive in the otorhinolaryngological field [in German]. *HNO* 2008;56: 509–518.
8. Lechner M, Sutton L, Fishman JM, et al. Otorhinolaryngology and diving-part 2: otorhinolaryngological fitness for compressed gas scuba diving: a review. *JAMA Otolaryngol Head Neck Surg* 2018;144: 259–263.
9. Backous DD, Dunford RG, Segel P, Muhlocker MC, Carter P, Hampson NB. Effects of hyperbaric exposure on the integrity of the internal components of commercially available cochlear implant systems. *Otol Neurotol* 2002; 23:463–467; discussion 467.
10. Kompis M, Vibert D, Senn P, Vischer MW, Hausler R. Scuba diving with cochlear implants. *Ann Otol Rhinol Laryngol* 2003;112:425–427.
11. Zeitler DM, Almosnino G, Holm JR. Stability of residual hearing and cochlear implant function following multiple scuba dives: case report. *Undersea Hyperb Med* 2018;45:371–376.