ORIGINAL ARTICLE
OTOLOGY
DOI: 10.5152/B-ENT.2021.21532

More than a quarter century of cochlear implantations: a retrospective study on 1161 implantations at the Antwerp University Hospital

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Cite this article as: Mertens G, Hofkens–Van den Brandt A, Boudewyns A, et al. More than a quarter century of cochlear implantations: a retrospective study on 1161 implantations at the Antwerp University Hospital. B-ENT 2 September 2021. 10.5152/B-ENT.2021.21532 [Epub Ahead of Print]

ABSTRACT

Objective: In this study, we aimed to describe the demographic profile of all 1161 implantations performed in the last 27 years, including sex, (evolution of) age at implantation, side of implantation, and rate of reimbursed cases; to identify the differences between the adult and the pediatric cochlear implant (CI) population; to describe the etiology of hearing loss in the adult and pediatric CI population; and to investigate the number and causes of the re-implantations.

Methods: We performed a retrospective demographic analysis of all 1161 cochlear implantations performed at the Antwerp University Hospital between August 1993 and November 2020.

Results: The vast majority of the adult population presented with bilateral sensorineural hearing loss (89%) of an unknown etiology (52%) and was unilaterally implanted at a median age of 60 years. In the pediatric population with congenital profound hearing loss, the median age at first implantation decreased significantly over time. During the past five years, the median age at first implantation was 12 months or younger for children with congenital hearing loss. A genetic cause was the most common etiology in children with bilateral sensorineural hearing loss (53%). Of all implantations, 4% were re-implantations. Re-implantations were performed on average ten years after the first implantation, and the most common reason for re-implantation was implant failure (76%).

Conclusion: This study described the profile of 1161 adult and pediatric implantations between the start in 1993 and 2020 that were performed at the Antwerp University Hospital in parallel with the evolution of the Belgian reimbursement criteria.

Keywords: Aetiology SNHL, cochlear implants, paediatric CI, reimbursement cirteria, sensorineural hearing loss

Introduction

According to the World Health Organization, around 466 million people worldwide have disabling hearing loss today. Moreover, given the growing and aging demographic trends, the prevalence of disabling hearing loss is expected to increase significantly over the next few year (1). Patients with severe or profound sensorineural hearing loss (SNHL), who cannot adequately benefit from properly fitted hearing aids, can be treated surgically with a cochlear implant (CI). Cochlear implants are widely regarded as the most successful electronic neural prosthesis as they are able to replace the complex function of the inner ear. Today, an estimated 700,000 hearing impaired patients benefit from a CI globally, a number that is significantly higher than the numbers for all other types of neural prostheses combined (2).

The development of the multichannel CI with the today's technologies started in the early 1800s when Alessandro Volta discovered that electrical stimulation of the auditory system could convey meaningful sounds to the brain (3). This breakthrough inspired Dr. William F. House to develop a practical and reliable way to treat deafness using electrical stimulation of the cochlea. In 1961, he implanted two bilaterally deaf patients with a sin-

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Received: June 1, 2021 **Accepted:** June 17, 2021 **Available Online Date:** September 2, 2021
Available online at www.b-ent.be

gle-electrode gold wire. The patients were able to sense environmental sounds via electrical stimulation of this single electrode but could not understand speech. Thereafter, multiple attempts were made worldwide to successfully provide electrical stimulation to the auditory nerve using an electrode array inserted into the scala tympani. However, as recently as the early 1980s, only a few pioneers believed that CIs would allow more than just sound perception. By the late 1980s, they were proven right with the introduction of multi-channel implants (4). The consensus statement from the National Institutes of Health reported in 1988 that about one in 20 patients with CI could carry out a normal conversation without lip reading (5). Several university-industry partnerships around the world began to develop multi-channel CIs, and the commercialization period was launched. International initiatives by Chorimac (France), Laura (Belgium), Nucleus (Cochlear, Australia), MED-EL (Austria), Clarion and Ineraid (United States of America) allowed for early advances of the multi-channel CI. At present, tremendous progress has been made in the development of the design and performance of CIs.

Although CI has proven to be an effective and safe treatment for severe or profound SNHL today, only less than 10% of eligible patients receive a CI. Therefore, D' Haese and colleagues concluded that additional efforts are required to ensure that a larger number of patients has access to this technology. Data from their surveys support the need for awareness activities for both professionals and the general population to improve knowledge of what a CI is and how it can help (6).

In high income countries, CIs are generally funded by national healthcare or insurance systems (6). In Belgium, the National Institute for Health and Disability Insurance (NIHDI-RIZIV-INAMI) sets the reimbursement fees and the conditions as to who is eligible for reimbursement of the different treatment options for several pathologies, including severe or profound SNHL. In October 1994, NIHDI introduced reimbursement for CIs in adults and in children with bilateral total SNHL (Table 1). More than 10 years later, in March 2006, these reimbursement criteria were revised. Profound SNHL was defined as, in the best ear, 1) pure tone average (PTA) of 85 dB HL or worse at 0.5, 1, and 2 kHz; 2) threshold of peak V of the auditory brainstem responses (ABR) at 90 dB nHL or worse; and 3) little or no benefit from hearing aids. Post lingually deafened patients' phoneme score, using monosyllabic words at 70 dB SPL, could not exceed 30% with hearing aids.

Main Points:

- The study described the demographic profile of all 1161 implantations performed in the last 27 years in the Antwerp University Hospital, in parallel with the evolution of the Belgian reimbursement criteria.
- The adult population presented with bilateral sensorineural hearing loss (89%) of an unknown etiology (52%) and was unilaterally implanted at a median age of 60 years.
- A genetic cause was the most common etiology in children with bilateral sensorineural hearing loss (53%).
- In the pediatric population with congenital profound hearing loss, the median age at first implantation decreased significantly over time. During the past five years, the median age at first implantation was 12 months or younger for children with congenital hearing loss.

From then on, post-implantation auditory training and follow-up were reimbursed until the age of 18 years for children and two years for adults. As hearing technology evolves rapidly and as evidence is growing for specific cases, NIHDI regularly receives new demands from manufacturers, clinicians, and patients to broaden or adjust the reimbursement criteria for cochlear implantation. On the basis of encouraging research data from bilateral implantations in children, contralateral implants in children younger than 12 years was reimbursed by February 2010. For example, the study from Scherf et al. and Van Deun et al. reported that bilateral cochlear implantation resulted in improvements in hearing thresholds, sound localization, and speech perception in quiet and in noise (7, 8). Moreover, the indication for a contralateral CI has been broadened to include children between the age of 12 months and 18 years with auditory neuropathy spectrum disorders (ANSD). Patients with ANSD have normal functioning outer hair cells, but lesions affecting the auditory synapse or the auditory nerve that can result in SNHL and in particular poor speech recognition. Pure tone thresholds in these patients can still be moderate to good, but their speech recognition scores are poorer than expected according to their pure tone audiograms. Oto-acoustic emissions are typically present in patients with ANSD, but ABRs are largely abnormal or absent. Because most of these patients with ANSD do not fulfil the standard inclusion criteria for CI, a reimbursement exemption was made for patients with ANSD (9, 10). In case of bilateral post-meningitis deafness, the contralateral CI is reimbursed up to the age of 18 years. It is known that in up to 90% of patients with post meningitis deafness, neo-ossification obliterates the endolymphatic and perilymphatic spaces. This stage, *labyrinthitis ossificans*, can occur as early as four weeks after the onset of meningitis. Therefore, early and bilateral cochlear implantation in all patients with post meningitis deafness is supported by many studies to improve the likelihood of full electrode insertion (11). Since April 2015, cochlear implantation is reimbursed in children (< 12 years old) with asymmetric hearing loss as well, but only if there is profound hearing loss in the worst ear ($PTA_{0.5,1,2\,kHz} \geq 85$ dB HL and threshold of ABR peak V ≥ 90 dB nHL) and severe hearing loss in the best ear ($PTA_{0.5,1,2\,kHz} \geq 60$ dB HL and threshold of ABR peak V ≥ 65 dB nHL), with maximum 30% speech understanding at 70 dB SPL in the best aided condition.

Not only scientific evidence on the advantages of bilateral cochlear implantation in children has been accumulating, an association between optimum communication outcomes and earlier access to cochlear implantation has been documented in several studies as well (12, 13). Receiving a CI early in a child's life increases the likelihood to achieve the best achievable speech and social and language skills for an individual child. Most recent studies support CI provision earlier than 12 months of age for children with severe or profound SNHL. Early implantation in these children allows for optimal speech perception and subsequent language acquisition and speech production accuracy. The study by Dettman and colleagues is very promising and showed that 80% of their prelingually deaf cohort, who received their first CI before the age of 12 months, demonstrated receptive vocabulary knowledge within the normal range at the time of school entry (12).

After the primary refinements in 2006, it took a long time before the reimbursement criteria were revised again in Belgium.

An international survey from Vickers et al. (14) in 2016 found that the United Kingdom and Belgium had the most conservative audiological criteria for CI at that time. The current reimbursement criteria in Belgium were finally expanded in December 2019. The average hearing threshold in the best ear was lowered from ≥ 85 to ≥ 70 dB HL, measured on three of four frequencies (0.5, 1, 2, and 4 kHz); the free field monosyllabic word score at 70 dB SPL was adjusted from 30% to 50%, but now applies to the unaided condition; and the ABR test indicates a threshold of peak V ≥ 75 dB nHL (instead of ≥ 90 dB nHL). For children with asymmetric hearing loss, the PTA in the worst (≥ 85 dB HL) and the best ear (≥ 60 dB HL) should now be based on three of four frequencies (0.5, 1, 2, and 4 kHz), instead of the previous criterion of 0.5, 1, and 2 kHz. Their speech understanding, measured in free field at 70 dB SPL in the unaided condition, should not exceed 50%. An overview of the Belgian reimbursement criteria for CI is provided in Table 1.

Methods

Study objectives

A retrospective analysis was performed to answer the following research questions; 1) What is the demographic profile of all 1161 implantations performed at the Antwerp University Hospital (UZA) in the last 27 years, including sex, (evolution of) age at implantation, side of implantation, and rate of reimbursed cases?; 2) What are the differences between the adult and pediatric CI population?; 3) What is the etiology of hearing loss in the adult and pediatric CI population?; and 4) What is the proportion of the re-implantations in relation to all the implantations?

Subjects

Subjects were included in the analysis if they met the following inclusion criteria; implanted with a multi-channel CI, and implantation was performed at UZA, which excluded patients who received follow-up care at UZA, but are implanted elsewhere. There were no age restrictions for inclusion. In total, 1161 implantations were registered in the local custom CI database of UZA.

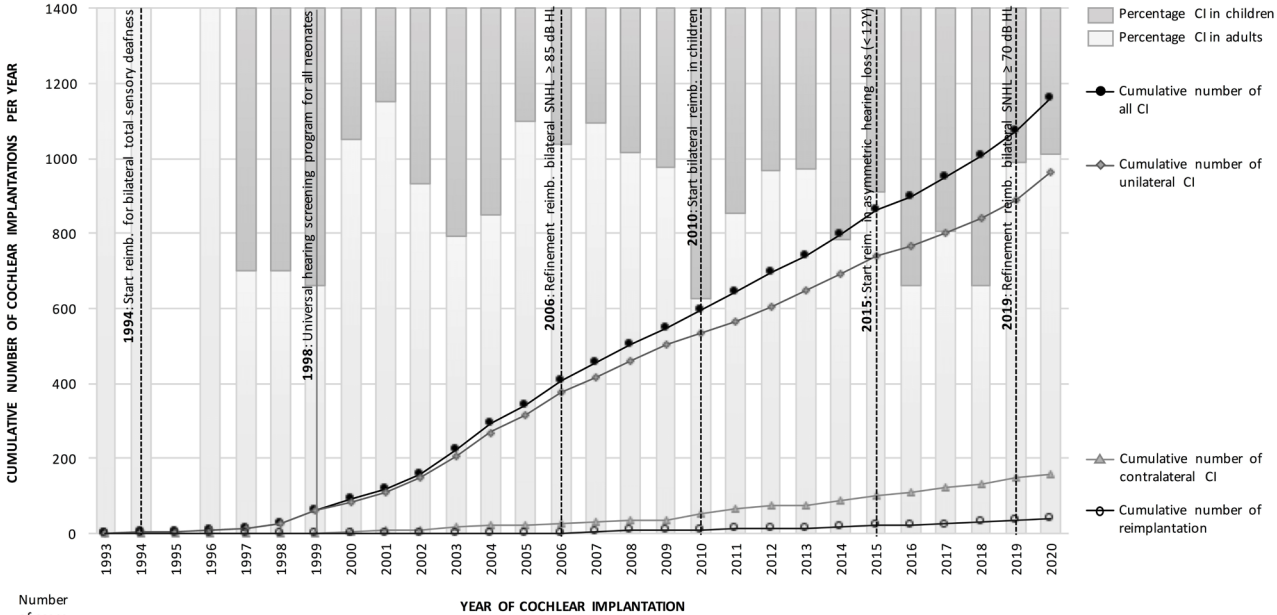
To investigate the evolution of the median age at first implantation in the pediatric population, the following pediatric cases were included for analysis; children with confirmed congenital severe or profound SNHL and with insufficient functional benefit of hearing aids. Children with inconclusive or missing data in their patient records to confirm the congenital nature of the hearing loss were excluded from analysis, as well as children who moved to Belgium at a later age because of an immigration background (n=10).

Ethics

The study reported on retrospective demographic data. Therefore, the study was conducted in accordance with the recommendations of the ethics committee of UZA that waived the need to obtain informed consents for this study.

Statistical analysis

Data were collected in a custom Microsoft Excel database (Microsoft Office Professional Plus 2016, MicrosoftCorp., Redmond, Washington) and analyzed in IBM Statistical Package for Social Sciences software version 24 (IBM Corp., New York,



Number of cases	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Paediatric	0	0	0	0	2	8	19	7	5	13	29	26	11	17	10	14	13	27	18	16	14	25	22	19	22	30	19	25
Adult	2	4	0	2	2	8	17	21	23	26	38	40	40	49	36	37	30	22	28	36	32	32	41	17	30	27	46	64
Total	2	4	0	2	4	16	36	28	28	39	67	66	51	66	46	51	43	49	46	52	46	57	63	36	52	57	65	89

Figure 1. Overview of the number of cochlear implantations performed in the Antwerp University Hospital since 1993
Cumulative numbers for all implantations with filled dots (·), unilateral implantations with grey diamonds (◆), and contralateral implantations separately with grey triangles (▲) are presented over time. Cumulative numbers for re-implantations are displayed with open dots (○). Implementation and refinements of the Belgian reimbursement criteria are presented by dotted lines (----). The proportion of children in relation to the total cumulative number of all implantations is presented by the dark shaded area, whereas the proportion of adults is represented by the light shaded area (in percentage). The number of pediatric and adult patients per year are shown in the table at the bottom.

Table 1. Overview of the Belgian reimbursement criteria for cochlear implantation

		October 1994	March 2006	February 2010	April 2015	December 2019
Adults > 12Y	Pure Tone Average Best Hearing Ear	Bilateral total sensory deafness	≥ 85 dB HL	Unchanged	Unchanged	≥ 70 dB HL
	Included frequencies PTA		.5, 1, 2 kHz			.5, 1, 2, 4 kHz (average of 3 freq.)
	Phoneme score speech audiometry		≤ 30% at 70 dB SPL			≤ 50% at 70 dB SPL
	Test condition		Aided			Unaided
	Threshold peak V in ABR		≥ 90 dB nHL			≥ 75 dB nHL
	Bilateral implantation?	No	No	No	No	No
Children < 12Y	Pure Tone Average Best Hearing Ear	Bilateral total sensory deafness	≥ 85 dB HL	Unchanged	Unchanged	≥ 70 dB HL
	Included frequencies PTA		.5, 1, 2 kHz			.5, 1, 2, 4 kHz (average of 3 freq.)
	Phoneme score speech audiometry		≤ 30% at 70 dB SPL			≤ 50% at 70 dB SPL
	Test condition		Aided			Unaided
	Threshold peak V in ABR		≥ 90 dB nHL			≥ 75 dB nHL
	Bilateral implantation?	No	No	Yes	Yes	Yes
	Asymmetric hearing loss	No	No	No	Yes	Yes

PTA: Pure Tone Average, ABR: Auditory Brainstem Respons, Y: Year

Table 2. Frequency table of implantations performed in children and adults (according to bilateral deafness, unilateral deafness, and re-implantations)

	Adults		Children		All	
Bilaterally deaf	668	89%	397	97%	1065	92%
- Unilateral implantation	636	85%	276	67%	912	79%
- Contralateral implantation	32	4%	121	29%	153	13%
Unilaterally deaf	43	6%	2	0%	45	4%
Reimplantation	39	5%	12	3%	51	4%
Total	750	65%	411	35%	1161	

NY). Given the skewed distribution, non-parametric descriptives were used to define age at implantation. Descriptive analyses of the etiologies were based on the total number of subjects and not on the number of implantations to avoid double counting in case of bilateral or re-implantations. Etiologies of SNHL were categorized in predefined groups.

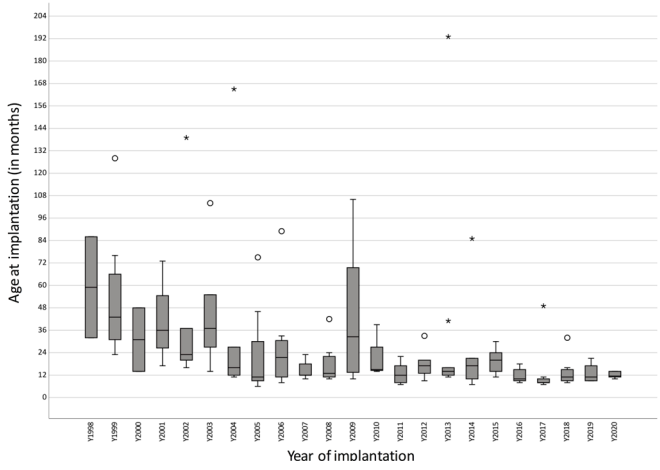


Figure 2. Overview of evolution of the age at implantation in all pediatric patients with confirmed congenital severe to profound sensorineural hearing loss (n=135)
Box plots represent the minimum, first quartile, median, third quartile, and maximum age at implantation per year (1998–2020) expressed in months. Out values (values between 1.5 * interquartile range and < 3 * interquartile range) are presented with a circle and extreme values with a star (values > 3 * interquartile range)

Results

Demographic profile of 1161 implantations

An overview of all 1161 cochlear implantations performed at UZA between August 1993 and November 2020 is provided in Figure 1. The first cochlear implantation at UZA was performed on August 08, 1993, in an adult with acquired bilateral profound SNHL with the LAURA system (Leuven and Antwerp Universities Research Auditory, Philips Hearing Implants), an eight bipolar or 16 monopolar channels device.[1] Later, CIs from the following companies were used for implantation: Advanced Bionics (Santa Clarita, California, USA), Cochlear Nucleus (Sydney, Australia), MED-EL (Innsbruck, Austria) and Oticon Medical - Neurelec (Vallauris, France). Six hundred and fifteen (53%) implantations were performed in women and 546 (47%) in men. Six hundred and forty implantations (55%) were performed in the right ear and 517 (45%) in the left. In

Table 3. Overview of the etiologies of sensorineural hearing loss in the adult cochlear implant population (%)

Unknown				370	54,5%
Genetic, non-syndromic				113	16,6%
	COCH	54	7,95%		
	Genetic other	52	7,66%		
	GJB2	7	1,03%		
Menière's disease			35	5,2%	
Otosclerosis				30	4,4%
Meningitis			21	3,1%	
Trauma			20	2,9%	
Cholesteatoma			13	1,9%	
Ototoxicity (Chemo, Aminoglycosides, ...)			13	1,9%	
Genetic, syndromic			10	1,5%	
	Usher's syndrome	5	0,74%		
	Alstrom syndrome	1	0,15%		
	Cogan syndrome	1	0,15%		
	BOR syndrome	1	0,15%		
	Cornelia de Lange syndrome	1	0,15%		
	Pendred syndrome	1	0,15%		
Schwannoma			9	1,3%	
Noise exposure			9	1,3%	
Autoimmune disorder				8	1,2%
Iatrogenic				7	1,0%
Congenital infections			4	0,6%	
	Rubella	3	0,44%		
	Cytomegalovirus infection	1	0,15%		
Inner ear malformation				4	0,6%
Central nervous system disorders			4	0,6%	
Labyrinthitis			3	0,4%	
Otitis Media			3	0,4%	
Mumps			1	0,1%	
Auditory neuropathy			1	0,1%	
Cholesterine granuloma			1	0,1%	
TOTAL				679	100%

95% of patients, the implantation was reimbursed by NIHDI or another foreign insurance company. The remaining 5% did not meet the reimbursement criteria (contralateral CI in adults, CI in unilateral hearing loss, or hearing too good according to the CI reimbursement criteria) but chose to pay for implantation themselves or were covered by a research grant.

Demographic profile of adult versus pediatric population

A total of 750 (65%) implantations were performed in adults and 411 (35%) in children. The majority (92%) of the implantations was performed in patients with bilateral deafness and only 4% in patients with single-sided deafness (SSD). As a consequence of the reimbursement for bilateral implantation in children, the proportion of contralateral implantations was higher in children (29% of all pediatric implantations) than in adults (4% of all adult implantations). Three (9%) of the 32 adult contralateral implantations were performed in patients with Usher syndrome, where reimbursement was obtained through the special solidarity fund. An overview can be found in Table 2.

In the adult population, the median age at implantation was 60 (18-94) years. The youngest child implanted in our center was six months and 14 days old on the day of first implantation and suffered from post-meningitis SNHL. The overview of the age at first implantation that is presented in Figure 2 is according to 135 pe-

Table 4. Overview of the etiologies of sensorineural hearing loss in the pediatric cochlear implant population (%)

Genetic, non-syndromic				68	35%
	GJB2	43	21,94%		
	MYO15A	7	3,57%		
	TMPRSS3	6	3,06%		
	TMC1	4	2,04%		
	TRIOBP	3	1,53%		
	ESRRB	2	1,02%		
	MARVELD2	1	0,51%		
	POU3F4	1	0,51%		
	CIB2	1	0,51%		
Genetic, syndromic				36	18%
	Usher's syndrome	7	2,45%		
	Waardenburg syndrome	7	2,45%		
	Pendred syndrome	7	2,45%		
	CHARGE syndrome	3	1,05%		
	Distal renal tubular acidosis 2 with progressive SNHL	3	1,05%		
	Jervell-Lange-Nielsen syndrome	2	0,70%		
	Wolfram syndrome	2	0,70%		
	Bartter syndrome	1	0,35%		
	BOR syndrome	1	0,35%		
	GJB2 syndromic	1	0,35%		
	Kabuki syndrome	1	0,35%		
	Progeria like syndrome	1	0,35%		
Congenital infections				32	16%
	Cytomegalovirus infection	31	10,84%		
	Rubella	1	0,35%		
Unknown, after complete etiological work-up				22	11%
Meningitis				16	8%
Inner ear malformation				10	5%
Central nervous system disorders				8	4%
	Other central nervous system disorders	3	1,05%		
	Hyperbilirubinemia	3	1,05%		
	Perinatal factor	2	0,70%		
Metabolic disorder				4	2%
TOTAL				196	100%
Unknown, after incomplete etiological work-up				23	
Unknown, no etiological work-up				67	

diatric patients with confirmed congenital SNHL. In the last five years (2016-2020), the median age at first implantation was 12 months or younger. Before that time, from 2010 until 2015, the median age at first implantation was below 24 months. During the first years of cochlear implantation (1998-2009), the median age ranged from almost five years to one year.

Overview of etiologies of SNHL in adult versus pediatric population

In the majority (54%) of the adult patients with CI, the etiology of SNHL was unknown. This proportion covered patients with no, incomplete, and complete etiological workups. Genetic origins of SNHL were reported in 17% of patients, with *DFNA9*

Table 5. Overview of the reasons for re-implantation performed in adults and in children

	Adults		Children		All	
Device failure	29	74%	10	83%	39	76%
Trauma	2	5%	2	17%	4	8%
Medical indication	3	8%	0	0%	3	6%
Poor performances	3	8%	0	0%	3	6%
Old generation	2	5%	0	3%	2	4%
Total	39		12		51	

being the most common (8% of all adult cases). *DFNA9* is a cause of autosomal dominant non-syndromic late-onset SNHL associated with progressive bilateral vestibulopathy (16, 17). It is caused by mutations in the *COCH* gene, mapped to chromosome 14 (14q12-q13). A common ancestor in Belgium and the Netherlands explains the relatively high reported prevalence of *DNFA9* in the study population. Other registered causes of SNHL in the adult CI population, each of which explains more than 2% of all cases, are Meniere's disease (5%), otosclerosis (4%), meningitis (3%), and trauma (3%). Etiology of SNHL was categorized as unknown after complete etiological workup in 22 children, after incomplete workup in 23 children, and after no workup in 67 children. An overview of the etiologies of severe or profound SNHL in the adult population can be found in Table 3.

Genetic causes of SNHL were reported to be the most common in the pediatric CI population (35% non-syndromic and 18% syndromic). Mutations in *GJB2* (DFNB1A, encoding the Connexin26 gene) accounted 22% of all pediatric patients (18). Cytomegalovirus was found to be the leading non-genetic cause, explaining 11% of the pediatric cases. Given the historical nature of the study, the number of unknown etiologies in the pediatric CI recipients is relatively high (90 of the 286 cases) as in the adult population. A detailed overview of the pediatric etiologies of severe or profound SNHL can be found in Table 4**.**

Re-implantation cases

Of all 1161 implantations collected across a 27-year period, 51 (4%) were re-implantations. The mean age at re-implantation was 44 (2-90) years and occurred on average 10 (0-21) years after first implantation. The main reason for re-implantation was device failure (in 76% of patients). Trauma explained 17% of the re-implantations in children and only 5% in the adult population. In three adult patients, re-implantation was indicated because the outcomes after the first implantation were worse than anticipated. Because of persistent inadequate outcomes in these patients and emerging progressive neurological symptoms, the etiologies were reassessed by the team and assigned to neurodegenerative diseases. In another three adult patients, there was a medical reason for re-implantation: two infected CIs with a retroauricular fistula and one ossified case with electrode misplacement (Table 5). In Belgium, when the internal implant fails within ten years after implantation, the warranty covers the costs for re-implantation. Patients with CI are advised to insure the implant in the event of trauma. Re-implantations more than ten years after the first implantation are covered by NIHDI.

Discussion

In total, 1161 implantations were performed at UZA between 1993 and 2020. Since the start of the CI program in 1993, tremendous improvements in CI design were made, including the (number of) electrode contacts, the housing of the implant, (the size of) the external speech processor, the speech coding strategies, etc. The first implantation at UZA was performed with a LAURA system, which included eight bipolar electrode contacts and a body-worn speech processor that used a continuous interleaved sampling (CIS) speech coding strategy. Today, CI candidates are able to opt for CI systems with 12 to 22 electrode contacts and miniaturized behind-the-ear or single-unit speech processors using more refined speech coding strategies.

A demographic analysis was performed on all 1161 implantations to describe the profile of the adult and the pediatric CI population. Twice as many adults (65%) as children (35%) received a CI in UZA, which is similar to the Belgian numbers published by De Raeve and colleagues.[2] Although more adults are implanted, De Raeve et al. reported that less research data is available about this adult population and that only less than 10% of the adults who could benefit from CI have been treated. In addition to the expected effect on post implantation hearing outcomes, there is also growing evidence that CI has a positive effect on the cognition of this aging population (20). Against the background of the ageing and growing world population, future public campaigns are required to improve awareness of cochlear implantation in (older) adults. Given the reimbursement criteria for CI in adults, the majority of cases involved unilateral implantations in bilaterally severe or profoundly deaf adults. The refinements of the reimbursement criteria in 2006 and 2010 did not have a noticeable effect on the number of implantations. Despite the growing number of people who could possibly benefit from a CI, the number of implantations seemed to remain stable over time. This once again confirms the need to increase awareness to improve the knowledge about the possibilities of cochlear implantation. From 2006 (adjustment definition SNHL in Belgian reimbursement criteria) until 2018, there were on average 51 implantations per year. Future research will show whether the thorough reimbursement refinements in 2019 have a significant impact on the number of implantations. A first tentative increasing trend was observed in 2019 and 2020, with 65 and 89 implantations. Given the influence of the coronavirus disease 2019 pandemic on the number of implantations, the numbers may be higher in the coming years.

In a majority of the adult patients, the cause of SNHL was unknown. An etiological analysis of the pediatric population, however, reveals that a genetic etiology was the most common finding. This is similar to the findings of a study by Miyagawa et al. (21) in 173 CI recipients that showed that genetic factors were the most commonly reported cause of SNHL. These authors postulated that identification of the genetic background may facilitate the prediction of post-implantation performances.

In children with bilateral congenital SNHL, a complete etiological workup (including a search for genetic, environmental, and struc-

tural causes) is recommended. However, over the past 20 years, the etiological workup was refined several times reflecting new scientific evidence (22, 23). Currently, comprehensive genetic testing (according to targeted genomic enrichment and massive parallel sequencing) is the cornerstone of the etiological workup for bilateral congenital SNHL (24, 25). Recent data revealed a genetic cause in 50% of children with congenitally, profound SNHL. Moreover, the implementation of a comprehensive genetic testing including gene panels improved the overall diagnostic yield for children with congenital hearing loss considered CI candidates, to 86% (26). Similar to the findings reported by Dietrich and colleagues, cytomegalovirus was found to be the leading environmental cause of SNHL in the study (11% of all pediatric cases). The prevalence of congenital CMV infection (cCMV) is 0.2% to 2% of pregnancies (27). The most common long-term sequela is SNHL, occurring in approximately 1/10 of asymptomatic and 1/3 of symptomatic children with cCMV (28). Although advances are being made in prevention and treatment of CMV, improved awareness of the disease in both clinicians and patients is needed (29). Moreover, the majority of children with cCMV are not identified at birth, except for the most severely affected. Implementation of screening programs for detection of cCMV is being considered internationally in children with only mild clinical findings or those who are completely asymptomatic (30).

In 1998, the universal new-born hearing screening program (UNHSP) was implemented in Flanders. The screening is performed by Kind en Gezin (K&G), a governmental institution accessible to people living in Flanders and Brussels. Screening for hearing loss in newborns is one of K&G's tasks laid down in a decree (Act of the Flemish Community, May 29, 1984) and involves automated ABR combined with a comprehensive referral strategy to ensure fast-track access to early evaluation in a reference center. The coverage of K&G is very high: 94.2% of all children born in Flanders in 2019 received at least one hearing test by a K&G nurse in the maternity ward (31). Owing to early implementation of the UNHSP, this study has a very high number of children implanted early. Early access to sound can allow a child's speech and language development to be on par with normal-hearing peers, enabling a life of possibilities (12).

As a result of evolving, evidence-based indications for CI, reimbursement criteria have been refined over the past 27 years in Belgium. For example, expansions were introduced for bilateral cochlear implantation in children, cochlear implantation in asymmetric hearing losses, and patients with meningitis and ANSD. In addition, patients who do not meet the reimbursement criteria for CI can be reimbursed through the special solidarity fund in exceptional cases. For example, in our study cohort, this was the case for patients with Usher syndrome or with intracochlear schwannomas.

Before the last refinements of the Belgian reimbursement criteria in December 2019, Belgium had one of the most conservative audiometric criteria together with the United Kingdom. Today in 40% of the countries, including Belgium, bilateral cochlear implantation in adults is still only available through a self-funding route although the accompanied binaural benefits are well established (14, 32, 33). The same applies for cochlear implantation in SSD. There is growing evidence that CI in SSD restores binaural hearing and therefore improves sound localization, speech perception in noise and audibility (34). In patients with well-defined SSD, cochlear implantation has proven to be an effective treatment for ipsilateral incapacitating tinnitus (35). Although cochlear implantation received CE approval for the indication of SSD in adults and in children in 2013; to date, CI in SSD is not reimbursed in Belgium.

The analysis of the re-implantations included all generations of implant systems that were used between 1993 and 2020. As a result of improved technology and the fact that they have only been in circulation for a short time, the newer generations had lower failure rates. Implant failure was found to be the most common reason for re-implantation (in 76% of the re-implantations), which is similar to the findings from previous research (36). The finding from Arnolder and colleagues that head trauma occurred less in the adult population than in the pediatric population was confirmed in our study (5% in adults vs 17% in children) (37). The higher risk of head trauma and the more vulnerable skull anatomy advocates the need to consider implant immobilization in pediatric implantations. We strongly agree that reliability reporting is important to accommodate transparency of device and treatment failures (38).

In patients whose auditory nerve is severely hypoplastic or absent and in whom cochlear implantation is therefore not recommended, auditory brainstem implantation can be considered. In the study population, cochlear implantation was followed by auditory brainstem implantation in four (0.3%) patients. In two patients with inner ear malformation, the ABI was implanted in the contralateral ear and used in combination with the CI. In another two patients, the electrode array from the initial CI was only inserted partially owing to ossification, which resulted in insufficient auditory outcomes.

As patient numbers increase and indications for cochlear implants broaden with advances in the technical possibilities, there is a need for national and international structured and comprehensive collection of clinical data. Similar to advances in other fields, like cardiac pacemakers or knee and hip implants where the collection of data from everyday clinical routines is widely used, a comparable implant registry is lacking in the field of CI. First initiatives were for example introduced in France under the auspices of the French Health Authority (39). International and national registries could offer the possibility to investigate clinical effectiveness and economic aspects, to fulfil post-market observational study commitments for regulatory bodies, and to investigate the experience with cochlear implants throughout the device and patient lifecycle.

Ethics Committee Approval: The study reports on retrospective demographic data. Therefore, the study was conducted in accordance with the recommendations of the ethics committee of the Antwerp University Hospital that waived the need to obtain informed consents for this study.

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Peer-review: Externally peer-reviewed.

Author Contributions: Supervision – G.M., V.V.R.; Design – G.M., V.T., P.V., O.V., V.V.R.; Materials – A.H., E.C., A.B., P.G.; Data Collection and/or Processing – A.H., E.C., A.B., P.G.; Analysis and/or Interpretation – G.M., V.V.R.; Literature Search – G.M.; Writing Manuscript – G.M.; Critical Review – A.H., A.B., E.C., P.G., M.L., V.T., P.V., O.V., V.V.R.

Conflict of Interest: The authors have no conflict of interest to declare.

Financial Disclosure: The authors declared that this study has received no financial support.

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