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Cochlear Implantation in Cochlear Ossification: Retrospective Review of Etiologies, Surgical Considerations, and Auditory Outcomes

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Objectives: 1) To review the surgical and auditory outcomes and complications of cochlear implantation in cases with cochlear ossification. 2) To evaluate association between the extent and etiology of ossification to outcomes.
Study Design: Retrospective study.
Setting: Otology and skull base surgery center.
Subjects and Methods: Charts of 40 patients (42 ears) with cochlear ossification undergoing cochlear implantation were reviewed. Demographic features, operative findings, auditory outcomes, and complications were analyzed. Operative findings included extent of cochlear ossification, extent of drilling required to obtain patent cochlear lumen, approach (posterior tympanotomy/subtotal petrosectomy), electrode insertion (partial/complete, scala tympani/vestibuli), and complications. Auditory outcomes were assessed over a 4-year follow-up period using vowel, word, sentence, and comprehension scores. Patients were divided into groups (otosclerotic/non-otosclerotic and round window/basal turn ossification) for comparison of auditory outcomes. Outcomes were compared with 60 randomly identified controls (adults with postlingual deafness) who underwent implantation with no cochlear ossification.
Results: The median age and duration of deafness of patients was 54.39 and 27.15 years, respectively. Etiology of cochlear ossification was otosclerosis in 23 of 42 ears and mixed in 19 of 42 ears (chronic otitis media, temporal bone fractures, idiopathic, meningitis, Cogan's syndrome) with exclusive round window involvement in 54.7% of cases and the rest having partial or complete basal turn ossification. 59.5% ears underwent subtotal petrosectomy for implantation. Three patients underwent scala vestibuli insertion and five had incomplete electrode insertion. Auditory outcomes were comparable in otosclerotic and non-otosclerotic cases and in round window and basal turn ossification cases. No significant differences were observed in auditory scores when compared with controls with no ossification.
Conclusions: Cochlear implantation in cochlear ossification is feasible despite surgical challenges and modifications. Auditory outcomes in basal turn ossification appear to be comparable to cases with no ossification with extent of ossification having no significant association with outcomes. **Key Words:** Cochlear implantation—Cochlear ossification—Partial insertion—Scala vestibuli—Subtotal petrosectomy.

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Cochlear ossification appears to be the result of a plethora of inflammatory processes involving the cochlea (1–3) and to cochlear implantation itself around the inserted electrode (4). Varying degrees of cochlear ossification can occur in more than 10% of all cochlear implant (CI) candidates (5). Pathologies implicated in cochlear ossification range from meningitis (meningogenic) (1–3,6–11), otitis media (tympanogenic) (1,3,11), otosclerosis (1,2,12), autoimmune inner ear disease (3,13), and miscellaneous disorders such as trauma, labyrinthine artery occlusion, temporal bone tumors, and Wegener's granulomatosis (1,3,14). Neo-ossification has been described to be of two types, metaplastic and osteoplastic (2). While the metaplastic form (meningitis and otitis media) comprising of high cellularity, low osteoblasts, and ill-defined margins is confined to cochlear lumen with endosteal preservation, the osteoplastic form causes endosteal disruption (trauma and otosclerosis), leading to new bone formation that is lamellar, less cellular, with clear margins indistinct from the endosteal layer (2). This pathological differentiation carries surgical implications while implanting ossified cochleae. Though basal turn scala tympani (ST) has been observed to be the most common location of cochlear neo-ossification irrespective of pathology (1–3), otosclerosis differs from other

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pathologies in characteristic absence of endolymphatic hydrops and semicircular canals' ossification (1), a feature observed in other pathologies (1,3).

Cochlear ossification remains a challenge in cochlear implantation due to considerable modifications in the surgical techniques ranging from surgical approaches (posterior tympanotomy/transcanal atticotomy/subtotal petrosectomy) (9,14,15), choice of arrays (standard/compressed/double array) (7–9,14,15), extent of drilling (RW/basal turn/middle turn/circum-modiolar drill out) (7,11,14–17) to location and extent of electrode insertion (scala tympani/scala vestibuli) (partial/complete) (8,11,12,14,15,18,19). Markedly variable postoperative auditory outcomes (6–11) arise due to extent of electrode insertion, reduction in spiral ganglion cell count (1,3), higher impedances, and charge for electrodes (10) along with higher risk for electrode migration (20).

Though literature reports variable results for cochlear implantation in ossified cochleae, most reviews are based on postmeningitis ossification (6–10) or on individual pathologies such as autoimmune disorders (13) and otosclerosis (12). Meningitis has been associated with negative post-implantation speech outcomes, irrespective of ossification or extent of electrode insertion (21,22).

The current study was undertaken to evaluate the surgical and auditory outcomes of cochlear implantation in cochlear ossification and to compare results between otosclerotic and non-otosclerotic ossification, between grades of ossification and with controls from normal CI recipients with no ossification.

MATERIALS AND METHODS

Medical records were analyzed to identify CI recipients who underwent cochlear implantation with cochlear ossification due to all etiologies. Forty patients were identified with confirmed cochlear ossification who underwent implantation. Two patients underwent bilateral implantation leading to total of 42 ears. One patient with severely ossified cochlea postmeningitis had no identifiable cochlear lumen intraoperatively and an auditory brainstem implant (ABI) using the translabyrinthine approach was performed at the same sitting. This patient is excluded from the study group and details can be sought from our previous publication (23). Another patient with bilateral severe cochlear ossification post temporal bone fractures had received CI at another center, with no response till 3 years. The CI was removed 3 years after implantation and an ABI performed through a translabyrinthine approach for hearing rehabilitation. The same is also excluded from the study group. All patients had a 4-year minimum follow up period post-implantation. One patient with incomplete insertion was lost to follow up and is excluded from the audiological analysis. All patients exhibited postlingual hearing loss except one prelingually deafened child postmeningitis, the audiological results of whom are mentioned separately. This yields a surgical dataset comprising of 42 ears and audiological data analysis of 40 ears. Sixty postlingual deaf adults who underwent cochlear implantation with no cochlear ossification were identified as controls for comparison to the study group.

Patient records were analyzed to evaluate demographic features, duration, and onset of hearing loss. Preoperative high resolution computed tomography (HRCT) and magnetic resonance imaging (MRI) scans were obtained for all patients to ascertain patency of cochlear lumen, unless specific contraindications for MRI existed. Operative records were analyzed to ascertain details of the implantation procedure, particularly to identify extent of drilling required to obtain patent cochlear lumen, approach used (posterior tympanotomy/subtotal petrosectomy), the instances of scala vestibuli (SV) insertion, extent of electrode array insertion (complete/partial), and intraoperative complications if any such as false tract insertions. The technique, indications, and follow up details of subtotal petrosectomy (STP) relevant to cochlear implantation can be referred to from our previous publications (15,24,25).

STP approach for a larger unhindered access to cochlea was used for basal turn ossification (BTO) or ossification extending beyond RW. Cases with chronic otitis media (COM) and temporal bone fractures involving otic capsule underwent STP regardless of the extent of ossification for permanent exclusion of the middle ear cleft from external environment and nasopharynx. Over the years, the institution has observed a lowered threshold for STP in cases of cochlear ossification due to the ongoing experience and comparable surgical outcomes from other indications as well (COM, temporal bone fractures, and abnormal anatomy without cochlear ossification). Though certain patients with BTO were implanted initially during early years with posterior or extended posterior tympanotomy (PT) approach, the same is reserved at present only for RW ossification. The decision for STP was always taken preoperatively with an informed consent and patients were informed of the need for extended radiological follow-up and esthetic concerns. No intraoperative conversion from PT to STP was done in the present cohort of patients. Diamond burr was used to drill in the direction of basal turn ST to obtain cochlear lumen, beginning from the RW or approximate location of RW in cases of obliteration (based on location of stapes and stapedius muscle). No separate cochleostomy or promontorial drilling was done to obtain cochlear lumen. Failure to obtain ST lumen till the beginning of ascending basal turn was used as an indication for SV insertion. Standard practices were to obtain postoperative x-ray control the next day after surgery, except in cases with BTO or electrophysiological discrepancies where peroperative x-ray was performed to assess implant placement. At present, however, all cases of cochlear ossification or revision implantations undergo peroperative x-ray control.

Postoperative audiological parameters observed were vowel, word, sentence scores, and comprehension scores measured over serial time points till 4 years, beginning from activation. Note was made of revision surgeries due to device failures or implant extrusions if any.

Auditory outcomes were compared between the study group (cochlear ossification) and control group (no cochlear ossification), between otosclerotic and non-otosclerotic ossification, and between grades of ossification.

RESULTS

The mean age of patients was 54.39 ± 2.58 years with 16 women and 24 men. The age at implantation ranged from 3 to 86 years with median age being 55 years. Twenty two right ears and 18 left ears were operated.

The mean and median duration of deafness were 27.15 ± 2.9 and 26.5 years, respectively. Figure 1 shows distribution of age at implantation and distribution of duration of deafness in years. A normal distribution of patients was present in both the groups despite the wide range in age and duration of deafness. Thirteen patients in this group had duration of deafness exceeding 30 years.

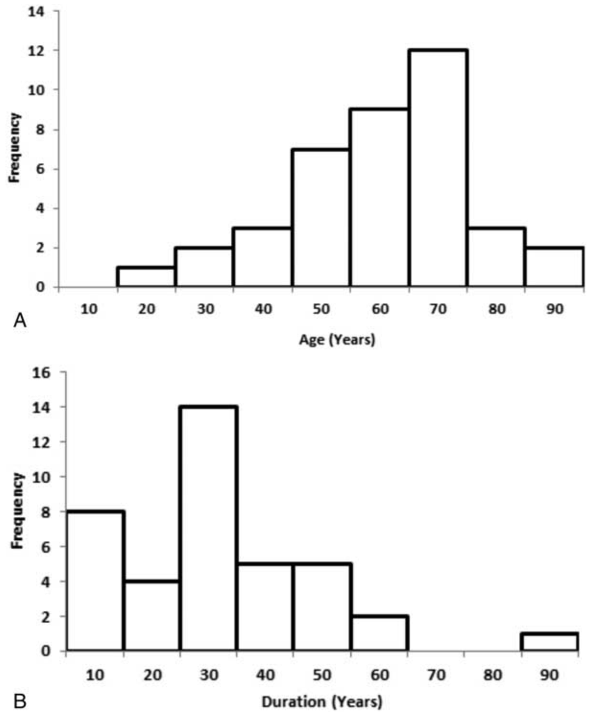

FIG. 1. *A*, Demonstrating the distribution of age at implantation and *B*, demonstrating distribution of duration of deafness in years in the study population.

The mean age of patients in control group was 57.9 ± 1.8 years (median 62 yr). The duration of deafness in control group ranged from 1 to 66 years with mean 18.6 ± 1.99 years (median 11 yr). Twenty one patients in control group had duration of deafness exceeding 30 years.

Surgical Results

Twenty three out of 42 ears (54.7%) had otosclerosis as the etiology of hearing loss in the study group, whereas, 19/42 (45.2%) ears in the non-otosclerotic category had cochlear ossification due to chronic otitis media, meningitis, trauma leading to temporal bone fractures, Cogan's syndrome, and idiopathic.

Twenty three out of 42 (54.7%) (16/23 in otosclerosis and 7/19 in non-otosclerosis group) ears in the study group had ossification limited to RW region and 19 had ossification of basal turn (45.2%) ranging from partial to total. Twenty five out of 42 (59.5%) (14/23 in otoslcerosis and 11/19 in non-otoslcerosis group) ears were implanted using the STP approach. Implants with straight electrode arrays were used in all patients with 25 MXM/Oticon (Chemin Saint Bernard, France) (Standard/CLA array), 9 Medel (Innsbruck, Austria) (Standard and Medium array), and 7 Cochlear (Sydney, Australia) (Slim Straight 422 array) devices. No specific electrode type was preferred except use of medium array from Medel for patients more than 65 years where the concerned brand was opted for. Single Advanced Bionics device was used in the patient with incomplete insertion that has been excluded from audiological results due to inadequate follow up. Table 1 describes the demographic and surgical details of patients, including etiology, surgical approach, extent of ossification, electrode insertion, and complications.

Complications

Table 1 briefly mentions the complications encountered in the study group. The cerebrospinal fluid (CSF) gusher was managed uneventfully using periosteal plugging. The false tract insertion of electrode array into superior semicircular canal (SSC) (otosclerosis group) was identified using a perioperative CT scanning and was corrected with reinsertion with confirmation of correct placement radiologically.

SV insertion was required in three cases where complete ossification of ST was encountered with no luminal patency till the ascending basal turn. All three patients had complete electrode insertion (Table 1). Two patients with otosclerosis and two with petrous fractures had incomplete electrode insertion with two electrodes outside the cochlea in all cases except in one case (petrous fracture) where only eight electrodes could be inserted after obtaining the cochlear lumen at the ascending basal turn.

Two revisions for device failures occurred in the otosclerosis group. Two cases deserve a special mention to highlight the surgical details.

In the first case, a patient with Cogan's syndrome with bilateral basal turn ossification underwent an ABI in another department without any trial for a cochlear implantation with no audiological benefit. He was implanted on the contralateral side using a CI with full electrode insertion into ST post basal turn drilling to identify patent lumen. Patient improved significantly following implantation with good speech outcomes. The ABI was switched off.

In the second case, a patient with history of COM was referred after an attempt at cochlear implantation with extensive basal turn ossification. On imaging, the electrode array was observed to be in the petrous carotid canal and not in the cochlea. The patient was taken up for surgery using the STP approach and after drilling, patent ST was observed at the beginning of ascending basal turn with a full uneventful electrode insertion confirmed radiologically. The array in carotid canal was transected and left as such.

The patient has had no complications on serial clinical and radiological follow ups.

One isolated case of bilateral facial nerve stimulation (FNS) post-implantation occurred in a patient of otosclerosis with modiolar spongiosis after 2 years of implantation. Cochlear devices were used on both sides with Slim Straight (422) electrodes. Programming alterations such as increasing pulse width and reducing current levels were employed initially followed by switching off one electrode on right side and three on left side (all mid array). No significant decrease in auditory performance was observed post switching off the electrodes with complete resolution of FNS till date.

Auditory Outcomes and Statistical Analysis

Figure 2 and Table 2 display the serial charting of pre- and postoperative vowel, word, sentence, and

TABLE 1. *Elaboration of patients with cochlear ossification with mention of etiologies, electrode insertions, scala inserted into, number of electrodes outside the cochlea, surgical approach used, and extent of ossification*

S. No.	Age	Sex	Side	Etiology/ Pathology	Approach	Extent of Ossification	Scala Inserted Into	Extent of Insertion	Complications If Any
N = 23	Mean = 58.2	M = 12 F = 11	R = 11 L = 12	Otosclerosis	STP = 14 PT = 9	RWO = 16 Partial BTO = 6 Complete BTO = 1	ST = 22 SV = 1	Twenty one full insertions Two partial insertions with two electrodes out	One FNS, one false tract insertion into SSCC, one CSF gusher, one bilateral FNS, one revision for extrusion, one revision due to device failure
24	40	M	R	Meningitis	PT	RWO	ST	Full	None
25	44	M	L	Traumatic	PT	RWO + partial BTO	ST	Full	None
26	41	M	R	Idiopathic	PT	BTO	ST	Full	None
27	58	M	L	COM	STP	RWO	ST	Full	None
28	57	F	R	Idiopathic	STP	RWO	ST	Full	None
29	30	F	L	Cogan's syndrome	PT	BTO	ST	Full	Pre-op ABI on opposite side previously outside
30	39	M	L	Meningitis	STP	Complete BTO (ST)	SV	Full	None
31	55	M	L	Traumatic	STP	RWO + partial BTO	ST	Partial, 2 outside	None
32	55	M	R	Traumatic	STP	RWO + partial BTO	ST	Full	None
33	49	F	R	Idiopathic	PT	RWO	ST	Full	None
34	86	M	R	COM	STP	RWO	ST	Full	None
35	61	M	R	COM	STP	Complete BTO (ST)	SV	Full	None
36	68	F	R	Idiopathic	PT	RWO	ST	Full	None
37	47	M	R	COM	STP	RWO + partial BTO	ST	Full	None
38	44	M	R	COM	STP	Extensive BTO	ST (pars ascenda)	Full	Electrode array in carotid canal from previous surgery, left as such with new array insertion in ST
39	3	M	R	Idiopathic	STP	BTO	ST (pars ascend)	Full	None
40[a]	57	F	L	Traumatic	PT	Extensive BTO	ST (pars ascenda)	Partial (only eight intracochlear electrodes)	Incomplete insertion
41	14	M	R	Meningitis	PT	RWO	ST	Partial (three electrodes out)	Incomplete insertion
42	55	F	L	COM	STP	RWO + BTO	ST	Full	Six electrodes inactive on activation

BTO indicates basal turn ossification; COM, chronic otits media; FNS, facial nerve stimulation; PT, posterior tympanotomy/extended posterior tympanotomy; RWO, round window ossification; SSC, superior semicircular canal; ST, scala tympani; STP, subtotal petrosectomy; SV, scala vestibuli.

[a]Excluded from audiological analysis due to loss of patient to follow-up

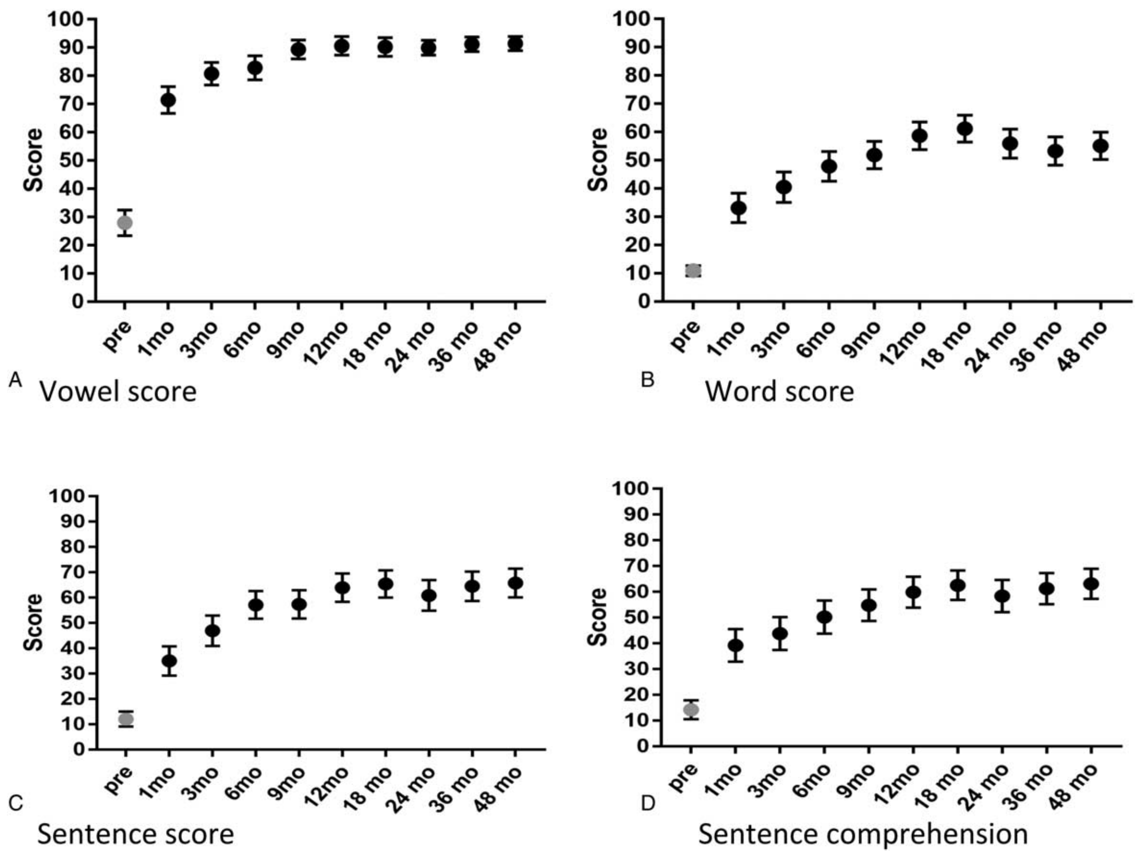

FIG. 2. Demonstration of serial charting of vowel (*A*), word (*B*), sentence (*C*), and comprehension scores from preoperative period to 1, 3, 6, 9, 12, 18, 24, 36, and 48 months post-implantation. mo indicates months; pre, preoperative.

comprehension scores observed 1, 3, 6, 9, 12, 18, 24, 36, and 48 months postsurgery.

Figure 3 displays the comparison of postoperative audiological outcomes between otosclerosis, non-otosclerotic groups, and between RW ossification and partial to complete BTO groups, and in controls with no cochlear ossification.

Compared with preoperative scores, auditory scores were highly statistically significant ($p < 0.01$) in all time periods measured with significance increasing 1 month onwards. Though vowel and word scores in otosclerosis showed a trend towards being higher than non otosclerotic pathologies, this difference was not statistically significant ($p = 0.09$ and 0.08, respectively). No significance was observed in sentence or comprehension scores over any time points or in vowel or word scores post 6 months of implantation between the two groups. No significance was observed between RW ossification and BTO groups.

When compared with the controls with no cochlear ossification, no significance could be observed in any of the parameters in any time points in the study group ($p > 0.05$).

For further analysis, subjects in the study cohort (ossified cochleas) were divided into two groups based on total duration of deafness being less or more than 30 years before surgical intervention. Maximum improvement in auditory scores achieved considering all time points up to 4 years was compared with these groups and was found nonsignificant ($p > 0.05$) by student's *t* test for all four parameters studied. Further, even though there was a trend to indicate that non-otosclerotic patients saw more improvement in scores when comparing patients with duration of deafness more than 30 years compared with those with duration of deafness less than 30 years (Fig. 4), this did not reach statistical significance as well ($p > 0.05$).

The single pediatric prelingual deaf patient demonstrated good vowel scores and initial word recognition in closed set surroundings at the last follow up and is constantly improving on audio visual therapy.

DISCUSSION

Cochlear implantation in cochlear ossification, though no longer a contraindication for the same, remains a challenging clinical scenario due to a range of surgical and audiological considerations and unpredictability associated with the outcomes. Table 3 presents a brief comparison of previous published series of cochlear implantation in cochlear ossification (6–11,18,26)

TABLE 2. *Pre- and postoperative mean auditory scores (vowel, word, sentence, and comprehension) measured in percentages for otosclerotic, non-otoslerotic, RWO, BTO, and controls with no cochlear ossification. All time points in months ranging from 1 to 48 months postoperative*

		Vowel Scores								
	Preoperative	1m	3m	6m	9m	12m	18m	24m	36m	48m
Otosclerotic	26.42	64.28	76.19	78.50	89.52	91.66	91.42	90.23	91.66	91.9
Non-otosclerotic	29.76	80.29	86.47	88.23	89.11	89.41	88.82	89.64	90.58	90.88
RWO	24.60	66.95	75.43	76.30	85.86	87.39	87.17	88.04	89.56	89.56
BTO	33	78.33	89	93	94.66	95.66	95	92.93	93.66	94.33
Controls	34.84	76.6	82.6	84.71	91	89.71	91.5	89.62	91.05	90.09
		Word Scores								
	Preoperative	1m	3m	6m	9m	12m	18m	24m	36m	48m
Otosclerotic	12.14	30.47	35.23	40.47	48.33	56.66	59.76	53.33	49.52	51.66
Non-otosclerotic	9.41	36.47	47.05	57.05	56.17	61.17	62.94	59.11	57.94	59.41
RWO	9.78	31.95	37.39	44.13	52.39	60.86	62.39	56.08	53.26	56.08
BTO	12.66	35	45.33	53.66	51	55.33	59.33	55.66	53.33	53.66
Controls	12.40	35.8	41.5	48.61	58.9	55.09	58.2	56.20	57.6	53.79
		Sentence Scores								
	Preoperative	1m	3m	6m	9m	12m	18m	24m	36m	48m
Otosclerotic	11.52	29.21	43	55.08	55.69	63.65	65.39	61.56	64.47	64.69
Non-otosclerotic	12.44	41.11	54.22	61.38	61.27	66.66	66.72	62.72	66.77	69.27
RWO	11.30	38.04	47.86	59.47	58.91	63.26	64.60	60.82	62.91	64.47
BTO	13.26	30.4	45.6	53.6	55	65	66.66	61	67	67.8
Controls	12.44	40.9	46.5	54.40	64.9	65.91	59.6	69.46	72.6	66.26
		Comprehension Scores								
	Preoperative	1m	3m	6m	9m	12m	18m	24m	36m	48m
Otosclerotic	13.91	38.69	40	47.60	55.78	59.56	63.47	59.78	61.52	63.26
Non-otosclerotic	14.66	40	49.66	54.2	53.33	60.33	61.2	56.2	60.87	62.86
RWO	13.91	38.69	40	47.60	55.78	59.56	63.47	59.78	61.52	63.26
BTO	14.66	40	49.66	54.2	53.33	60.33	61.2	56.2	60.86	62.86
Controls	13.18	39.7	45.1	55.71	62.5	68.43	64.7	66.85	67.8	64.71

BTO indicates basal turn ossification; RWO, round window ossification.

Demographics

Though traditionally considered a factor adversely associated with post-implantation speech perception outcomes, the effect of long duration of deafness and advanced age have become a less important factor over the past years, with evidence pointing that a duration of severe deafness of more than 40 years and age at implantation of more than 75 years still carries negative correlation with outcomes, though they continue to derive significant benefit from the procedure, more so during first 3 years post-implantation (27).

Though a wide range of disorders have been cited to cause ossification with relevance to cochlear implantation (1–3,14), literature is predominantly based on meningitis as the most frequent etiology (6–11,18,26), with a significantly high percentage of cochlear ossification mentioned in disorders like Cogan's syndrome (13) and otosclerosis (12). A recent review on 79 cases of implantation in cochlear ossification from China stated COM to be the cause of ossification in 35% of instances (11), a relatively high percentage, something mentioned in few pathologic studies as well (1,3). The maximum number of patients with cochlear ossification in the current study had otosclerosis (54.7%) as the causative pathology, with COM, idiopathic and petrous fractures as the most common etiologies (14.2, 11.9, and 9.5%, respectively) in non-otosclerotic causes. Though a significant reason for difference in distribution of etiologies could come from referral bias, it also represents, in our opinion, the change and expansion in criteria for implantation and reduction in incidence of meningitis. Advanced otosclerosis as an etiology has become a more acceptable indication for cochlear implantation (12,28), as has COM due to the introduction of STP in CI surgery (15,24,25).

Surgical Outcomes

Despite CT having a high specificity in diagnosing cochlear ossification and patency problems, many

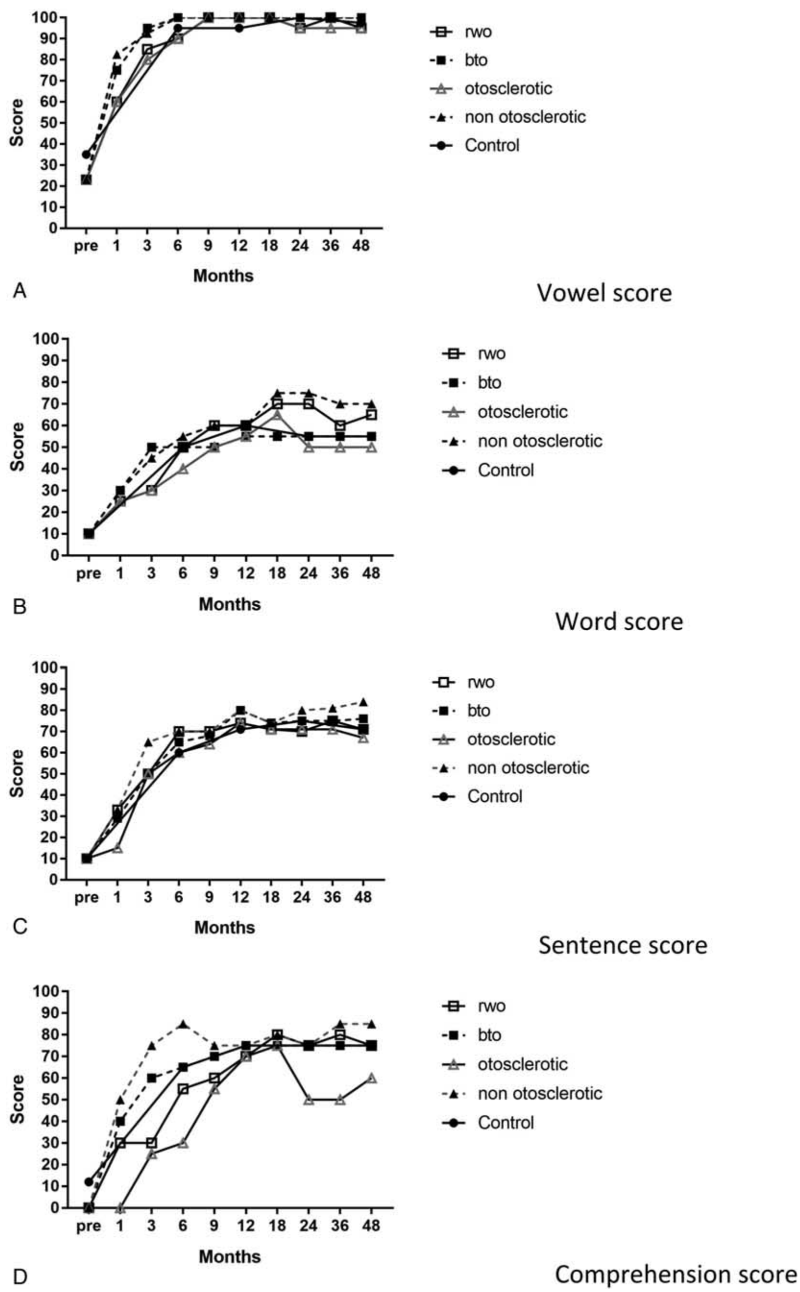

FIG. 3. Line diagrams depicting comparison of auditory outcomes between otosclerotic and non-otosclerotic group, as well as between round window ossification (rwo) and basal turn ossification (bto) subgroups and controls with no ossification. (*A*) Vowel score; (*B*) word score; (*C*) sentence score; (*D*) sentence comprehension.

authors have observed a much higher incidence and extent of ossification intraoperatively as compared with preoperative evaluation using CT (13,18). The addition of T2 MRI sequences to CT improves the sensitivity of diagnosing cochlear luminal obstruction (29) with the added potential to ascertain SV patency in cases of complete basal turn ST ossification (15).

The basal turn of ST has been postulated to be the most frequent site of cochlear ossification, regardless of the pathology, with the RW region always involved in tympanogenic ossification caused by COM (1,3). Isolated middle or apical turn ossification is very uncommon, though reported in literature (1,11), with SV ossification only developing after ossification of ST (1). While majority of cases in otosclerosis group (69.5%) had ossification limited to the RW region, most cases (63.1%) in non-otosclerosis group had ossification beyond RW involving varying amounts of basal turn.

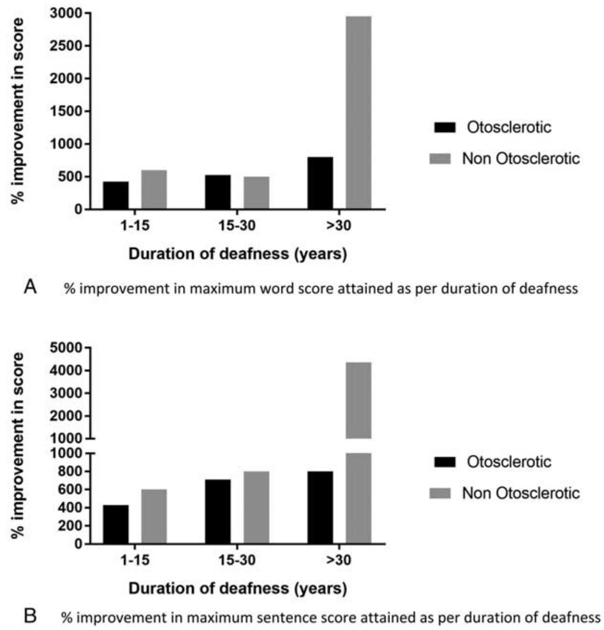

FIG. 4. *A*, % improvement in maximum word score attained as per duration of deafness. *B*, % improvement in maximum sentence score attained as per duration of deafness.

This is supported by pathologic studies where marked differences have been observed between ossification caused by otosclerosis and other causes, in terms of extent of ossification and selective involvement or sparing of intracochlear structures (1,2).

The extent and location of ossification has implications on choice of surgical approach, technique of drilling or electrode insertion, and choice of electrodes, with the aim being insertion of maximum number of electrodes. While critically important for prevention of implant extrusion in COM and meningitis associated with CSF leaks from petrous fractures, one of the most important contemporary indications of the STP approach, in our opinion, is an oriented access to the ossified cochlea, with rates of complications comparable to normal cochlear implantation (24,25,30). The isolated case referred with electrode insertion in carotid canal, in the current series, reaffirms the same and proves that limited access approaches cannot provide vascular control, should such a need arise.

Scala Vestibuli (SV) Insertion

In instances of ossification beyond RW, drilling was done till the beginning of ascending basal turn of cochlea to obtain patent lumen, failing which SV insertion was performed. Similar protocol has been observed in other studies (8,14,18,19) and no significant difference in outcomes has been observed in SV insertions as compared with ST insertions and the same may represent a more favorable scenario than middle turn drill-outs. In a review of 79 cases of ossified cochlea that underwent implantation (11), the authors stated no incidence of SV patency or insertion. They mentioned creating a ''second bony tunnel in basal turn'' parallel to tympanic facial nerve, above the primary basal turn tunnel for implantation in ossified cochleas. This, however, does not seem anatomically feasible as the ''second tunnel in basal turn'' appears to be the SV itself as the bony spiral lamina rotates along its own axis beyond 4.5 mm from the posterior lip of RW (31). ST insertion beyond this point would mean insertion of the array through the spiral lamina or basilar membrane itself (31). Though SV insertion potentially disrupts the Reissner's membrane (32,33), thereby abolishing the endocochlear potentials leading to residual hearing loss, this does not seem to be of much relevance in ossification patients due to absence of any significant residual hearing. Furthermore, due to the differences in tonotropic representation of ganglion cells in cochlear apex as compared with the base, an insertion beyond 360 to 450° does not seem required or justified, particularly in context to the monopolar stimulation strategy present in most modern implants (32).

Literature review (Table 3) suggests partial anterograde basal turn insertion (7,8), retrograde middle turn insertion using compressed array (9) and use of split or double array electrodes (7,8,10,14), as valid and comparable alternatives for electrode insertion in ossification extending beyond ascending basal turn of cochlea. While double array allows for more usable electrodes than partial insertion (7), partial insertion itself has not been associated with adverse outcomes given a certain threshold of active electrodes is in use, due to the provision of redundancy in electrode systems (7–9).

Five cases of incomplete electrode insertions were observed in the current study with two each from otosclerosis and temporal bone fractures and one from postmeningitis ossification. While no association of extent of ossification with incomplete insertion was observed in the current study, the solitary instance in temporal bone trauma of only eight intracochlear electrodes inserted, despite obtaining patent cochlear lumen post drilling, could be attributed to the bony spiral ligament injuries post trauma, a factor independent of cochlear ossification (34). Similarly, in a pathologic study, Lee et al. (35) observed perforation of spiral ligament with impingement on lateral scalar wall to be the most important factor associated with incomplete electrode insertion, and the junction of lower and upper basal turn to be the most critical location for the same (32). As the basilar membrane thins and widens towards the cochlear apex from base onwards, the risk of perforation increases with depth of insertion (32), explaining the four of five incomplete insertions that occurred towards the end of insertion. The extent of electrode array insertion depends on the amount of drilling required to obtain patent cochlear lumen, length of array itself and contact of the array with normal intracochlear structures (osseous spiral lamina, spiral ligament, basilar membrane), and potential disruption of intracochlear structures due to trauma (independent of ossification). Incomplete insertion is known to occur as much in cases

TABLE 3. *Selective literature of previous published literature on cochlear implantation in cochlear ossification highlighting patient features, etiologies, extent of ossification, surgical approach and insertional techniques, electrode choices, and extent of insertion, including scala and brief mention of auditory or electrophysiological outcomes*

Study	Number of Patients	Patient Demographics and Mode of Deafness	Etiology	Extent of Ossification/% of Patients with Ossification	Surgical Approach	Implantation Technique	Type of Electrodes Used	Insertion Issues (Extent of Insertion/False Tract Insertions)	Complications, If Any	Chief Auditory Outcomes
Bacciu S et al (18)	13	Postlingual, adults	Mixed (meningitis predominant)	23% RWO 77% BTO	N/A	Drill through,	Straight	10 SV insertions in BTO	N/A	Mean word scores for SV group 88%. No significant differences between ST and SV insertion
El-Kashlan et al (6)	21	Prelingual, children	Meningitis	42.8% minimal BTO 57.1% major ossification	PT	Drill through, partial BT insertions, circumodiolar drill-outs	N/A	Mean electrodes inserted for drill through, partial BT insertion and circumodiolar drill-outs as 18, 8.6, and 12.4, respectively	N/A	Mean SPC in three categories as 3..6, 3.2, and 3, respectively. Higher SPCs number of electrodes for children with ossification compared with those with none with meningitis
Roland et al (7)	20	Pre- and postlingual, adults and children	Mixed (meningitis predominant)	N/A	PT	Drill through with partial BT or partial BT with MT insertions	Straight, precurved and double array	Twelve partial insertions with mean electrodes inserted 14.7. Eight double array insertions with mean electrodes 18.1	None	Speech perception outcomes better in children than in adults, more usable electrodes in double array than in partial BT insertions
Nichani et al (8)	27	Pre- and postlingual, children	Meningitis	51% partial ossification, 48% gross ossification.	N/A	Drill through, drill through with partial BT with MT insertions	Straight, split array	Three SV insertions, seven double array insertions, three partial insertions	None	Better audiological performance scores for children with meningitis without ossification compared with ones with ossification. Good outcomes in partial insertions
Kirtane et al (26)	6	Pre- and postlingual, adults and children	Mixed (meningitis predominant)	N/A	PT	Drill through with partial BT and MT insertions, anterograde, and retrograde insertions	Double or split array	Mean electrodes inserted 18.3	None	Mean auditory performance scores 5.6 in children and nine in adults

(Continued on next page)

TABLE 3 *(Continued)*

Study	Number of Patients	Patient Demographics and Mode of Deafness	Etiology	Extent of Ossification/% of Patients with Ossification	Surgical Approach	Implantation Technique	Type of Electrodes Used	Insertion Issues (Extent of Insertion/False Tract Insertions)	Complications, If Any	Chief Auditory Outcomes
Senn P et al (9)	8	Pre- and postlingual, adults and children	Meningitis	Complete BTO with mean ossification length 7.4 mm	PT with combined transcanal	Apical retrograde insertions.	Compressed array	5/7 cases with electrode direction changes and tip rollovers	N/A	Average word scores better for anterograde basal turn insertions (controls) than apical retrograde insertions
Wang and Zhang (11)	79	Pre- and postlingual, adults and children	Mixed (meningitis and COM predominant)	26% RWO, 64% BTO, 9% ossification involving more than two turns	PT	Drill through, BT and MT anterograde insertions	Straight	All ''complete insertions''	None	Poor mandarin speech outcomes in severe ossifications and drill-outs over 6-month follow-up
Durisin et al (10)	56 ears, 34 with ossification	Pre- and postlingual, adults and children	Meningitis	62% partial ossification, 38% severe ossification	PT	Drill through, BT and MT insertions	Pre-curved and double array	Nine incomplete insertions	N/A	Increased impedances in the meningitis patients as compared with controls irrespective of ossification
Current study	42	Pre- and postlingual, adults and children	Mixed (Otosclerosis = 23, mixed = 19)	54.7% RWO, 45.2% BTO	PT 40.5% STP 59.5%	Drill through, drill through with partial BT insertions	Straight	5/40 cases with incomplete insertion. 3 SV insertions. One incidence of 6 inactive electrodes post full insertion	One false tract insertion into SSC (corrected), one revision for extrusion, one revision for device failure	Mean vowel scores >90% and mean sentence scores >60% at 1 year post-implantation

BT indicates basal turn; BTO, basal turn ossification; COM, chronic otitis media; MT, middle turn; PT, posterior tympanotomy/extended posterior tympanotomy; RWO, round window ossification; SSC, superior semicircular canal; ST, scala tympani; STP, subtotal petrosectomy; SV, scala vestibuli.

with no soft tissue or bony obstruction of scalar lumen than in cases with the same (31). Though STP provides a wider access to ossified cochlea, there appears no direct correlation or advantage of the same with regards to extent or completeness of electrode insertion, given the wide range of parameters insertion is dependent upon. The approach itself (STP/PT) is merely a method of access to patent cochlear lumen.

Though two cases with extreme and complete ossification had to be converted to an ABI due to absence of any implantable cochlear lumen, cochlear ossification, even complete, cannot be considered as a general indication for ABI, as suggested by few authors (36). The case in current study with subsequent cochlear implantation post an ABI confirms the same and is in accordance with our previous published multicenter results (37) on the valid indications and contraindications of ABIs in non-NF2 patients.

Auditory Outcomes

Cochlear implantation in cochlear ossification has been associated with variable outcomes, ranging from extent of ossification, pathology leading to ossification, extent and technique of electrode insertion to mode of deafness, and age at implantation. This is compounded by the fact that diseases such as meningitis may affect the central auditory pathways resulting in poorer outcomes, independently from ossification. The mean scores in vowel, word, sentence, and comprehension category improved significantly with time and are comparable with previous literature (Tables 2 and 3 and Fig. 2) (7–9,11,18). Though a definite association between extent of ossification and auditory outcomes has not been demonstrated (9), total cochlear ossification needing circumodiolar drill-outs has been associated with poor speech outcomes (11). No difference in outcomes could be demonstrated in the current study between cases with RW or BTO. Further, given the relatively small number of patients with BTO operated using either STP or PT, no attempt was made to correlate auditory outcomes with surgical technique and no valid conclusions could be drawn regarding the same. However, it can be assumed that analysis on a larger cohort of patients may demonstrate improved auditory outcomes in patients with BTO undergoing STP due to the consistency of obtaining access to cochlear lumen in absence of complications, as compared with PT, though eventually the number of intracochlear electrodes placed atraumatically and surviving spiral ganglion cell population would dictate auditory results. The slightly better vowel and word scores in otosclerosis group trending towards significance till 6 months post-implantation appear to be a result of the gradual progressive hearing loss in this category as compared with disorders such as meningitis and trauma, further substantiated with fact that no statistically significant differences could be observed post 1 year. Though highly varied word and sentence scores have been reported in double array (7) and apical retrograde insertions of compressed arrays (9), no cases requiring the same were encountered in the present study. The far lesser patients affected by meningitis also appear to have contributed to the favorable outcomes in the present study, as it is now known that central auditory pathways appear to have a much important role in post-implantation speech outcomes (27) than ganglion cell counts, something that can be commonly affected by meningitis (22). Though age at implantation and duration of deafness can be considered independent factors with negative correlation to post-implantation auditory performance, no statistical significance was observed in the present study with respect to both the parameters. This could be explained by the low auditory scores preoperatively, thus magnifying the eventual response in postoperative period when analyzing maximum scores achieved. Matterson et al. (28) in their review of cochlear implantation in otosclerotic patients remarked that age at implantation and duration of deafness only carry relevance in early postoperative and not long-term outcomes, and most such patients exhibit delayed, though eventual comparable outcomes to patients with lesser duration of deafness.

Limitations

Being a retrospective review with changing operative philosophies in the institution, certain deviations from protocols can be noted. Though reserved for BTO and ossification extending significantly beyond RW (>4.5 mm), STP was used in certain cases with ossification limited to RW as well. This can occur in presence of coexistent pathologies as well as discrepancies in radiological estimation and intraoperative confirmation of extent of cochlear ossification.

Further, being a retrospective analysis, the extent of cochlear ossification as noted from operative records has been an over simplification of the actual pathologic process and sub-categorization of the same as RW or BTO leads to dilution of data and analysis, which in ideal circumstances and in a prospective trial should be continuous and backed by measurements.

CONCLUSIONS

Cochlear implantation in cochlear ossification, though surgically challenging, is feasible in most cases, with STP greatly facilitating the same. Patent cochlear lumen can be obtained after drill through in most cases of RW or basal turn ossification till the ascending basal turn, with SV being a valid insertion option in cases of complete ST ossification. Postoperative imaging appears to be of vital importance in evaluating electrode position in the cochlea post-implantation in ossified cochleas. The extent of ossification in basal turn may not affect auditory outcomes if sufficient electrodes can be inserted in either scala. Though otosclerotic patients may initially perform better on word scores, no significant differences remain 1 year post-implantation, as compared with non-otosclerotic pathologies.

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