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Original Research Article

The study of hearing aid durability and microbial colonization in a coastal region in India

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ABSTRACT

Background: The global burden of hearing impairment necessitates the widespread deployment of hearing aids, which serve as the primary modality for audiological rehabilitation. However, the long-term efficacy, structural longevity, and hygienic safety of these devices are significantly challenged by extreme environmental factors. High-humidity coastal environments, characterized by atmospheric salinity and elevated temperatures, pose a unique and severe threat to the sophisticated microelectronics of these devices. Furthermore, these climatic conditions fundamentally alter the microenvironment of the external auditory canal, promoting the rapid growth of pathogenic bacterial and fungal biofilms on customized earmolds and acoustic domes. This dual threat frequently leads to device failure and recurrent auricular infections.
Methods: A comprehensive, mixed-methods observational study comprising a three-year retrospective analysis of audiology repair logs and a cross-sectional microbiological study of patient earmolds was conducted in the Department of ENT, Father Muller Medical College, Mangalore located in the monsoonal coastal region of Karnataka, India. Device failures were systematically categorized, and earmold swabs were cultured for aerobic bacteria, anaerobic bacteria, and fungal flora using established microbiological protocols.
Results: Analysis of 412 distinct hearing aid repair logs revealed a high incidence of moisture-related mechanical and electronic failures, predominantly affecting acoustic transducers. Receivers were the most frequently failed component (38.3%), followed closely by microphones (29.1%). The cross-sectional survey of 150 active earmolds demonstrated an alarming 78% microbial colonization rate. Fungal elements, particularly *Aspergillus spp.*, and opportunistic bacteria, notably *P. aeruginosa*, were the most prevalent isolates, frequently presenting as polymicrobial biofilms.
Conclusions: High-humidity coastal climates significantly accelerate the degradation of hearing aid microelectronics through galvanic corrosion and moisture ingress, while simultaneously fostering opportunistic, pathogenic microbial biofilms within the ear canal. Enhanced environmental structural protections, active dehumidification technologies, and highly stringent antimicrobial hygiene protocols are absolutely essential to sustain audiological rehabilitation and safeguard otologic health in tropical regions.

Keywords: Hearing aids, Biofilms, Equipment failure, Tropical climate, Otomycosis, Earmolds

INTRODUCTION

The integration of advanced digital health devices into daily life has fundamentally revolutionized the landscape of audiological rehabilitation. For the millions of individuals suffering from sensorineural hearing loss, modern digital hearing aids offer unprecedented improvements in speech perception, spatial awareness, and overall quality of life. However, the physical interface between the human body and the electronic device remains highly vulnerable to ambient environmental conditions. This vulnerability is particularly acute concerning the development of acute otitis externa and the physical degradation of the device itself.[1] Modern hearing aids are highly sophisticated microelectronic devices, integrating miniaturized balanced armature receivers, electret condenser microphones, and complex digital signal processing (DSP) chips within incredibly compact housings. While manufacturers have made significant strides utilizing hydrophobic nano-coatings and tighter structural seams to improve device durability, moisture-induced microelectronic failure remains a primary reason for device malfunction and clinical return.[2]

This inherent technological vulnerability is severely exacerbated in tropical and monsoonal coastal regions. These specific geographic areas are characterized by persistent, high ambient relative humidity-often exceeding 80% year-round-coupled with elevated ambient temperatures and pervasive atmospheric salinity. These combined environmental stressors exert a continuous, aggressive oxidative and osmotic stress on both the external casing and the internal circuitry of hearing aid components. Furthermore, the introduction of a hearing aid earmold or dome resides deep within the external auditory canal. This naturally dark, warm, and poorly ventilated anatomical space undergoes a drastic microclimatic shift upon occlusion, fundamentally altering the local microbiome over time.[3] The microscopic porosities and surface irregularities inherent in standard acrylic and medical-grade silicone earmold materials provide an ideal, nutrient-trapping scaffold for the rapid formation of microbial biofilms when continuously exposed to high humidity and human sweat.[4]

The establishment of these biofilms is not merely a hygienic nuisance; it is a significant clinical complication. Biofilms trap desquamated epithelial cells, cerumen, and environmental debris, slowly degrading the acoustic integrity of the sound bore and altering the frequency response of the hearing aid. More alarmingly, these biological matrices serve as a highly resistant, persistent reservoir for opportunistic pathogens, frequently leading to localized fungal infections, or otomycosis, and recurrent bacterial otitis externa.[5] Within the device hardware itself, the combination of warm, salt-laden moisture penetrating the battery housing or acoustic ports accelerates galvanic corrosion across the battery contacts and transducer wiring. This electrochemical reaction is particularly destructive to traditional zinc-air power interfaces, leading to crystalline buildup, voltage drops, and sudden processor failure.

The resulting clinical picture for audiologists and otolaryngologists practicing in tropical climates is frequently a frustrating, dual presentation of mechanical device failure and persistent, treatment-resistant otomycosis.[6] The financial burden of repeated out-of-warranty hardware repairs, coupled with the physical discomfort and medical costs of recurrent ear canal infections, frequently culminates in early hearing aid abandonment. This effectively nullifies the entire rehabilitation process, returning the patient to a state of auditory deprivation.[7] Despite the severity and high prevalence of these interconnected mechanical and biological issues, there remains a critical paucity of targeted, real-world clinical data evaluating specific hardware failure modes and microbial colonization profiles specifically within high-humidity coastal settings. Most existing durability literature relies on accelerated laboratory testing, which often fails to capture the complex, synergistic destructive nature of human sweat, cerumen, and continuous atmospheric salinity.

This study aims to address this significant gap in the literature by conducting a comprehensive, dual-arm evaluation of hearing aid longevity and earmold microbial colonization in a coastal tropical demographic. By quantifying both the mechanical and biological failure points, this research seeks to inform better clinical practices and highlight the need for regionally adapted audiological protocols.

METHODS

Study design, setting and ethical considerations

This study utilized a rigorously structured, mixed-methods observational approach, combining a retrospective analysis of clinical repair logs with a prospective, cross-sectional microbiological survey. The study was conducted in the Department of ENT, Father Muller Medical College, Mangalore, Karnataka, India from January 2019 to December 2021. This specific geographic region is defined by a classic tropical monsoon climate, noted for sustained high humidity, heavy seasonal rainfall, and continuous atmospheric salinity due to its proximity to the Arabian Sea. The study was approved by the institutional ethics committee on 10th May 2021 and the research protocol was strictly conducted in accordance with the ethical principles for medical research involving human subjects as outlined in the Declaration of Helsinki. For the prospective microbiological arm of the study, written informed consent was obtained from all participating patients after a detailed explanation of the swabbing procedure and the study's objectives.

Prospective microbiological survey of earmolds

A cross-sectional survey was conducted over a six-month period from June 2021 to November 2021, involving 150 consecutive adult patients attending the outpatient audiology clinic for routine hearing aid follow-ups, programming adjustments, or minor physical modifications. To ensure the microbiological data accurately reflected routine colonization rather than an acute clinical crisis, stringent exclusion criteria were applied. Patients presenting with active, discharging otitis media, perforated tympanic membranes, or a currently diagnosed and symptomatic episode of acute otitis externa were excluded from the swabbing protocol.

Using highly controlled, sterile techniques, specialized miniaturized swabs were utilized to sample the surface of the earmold, the internal aspect of the sound bore, and any integrated venting channels. The objective was to identify potential fungal and bacterial co-colonization deeply embedded within the acrylic or silicone matrices.[8] Two distinct swabs were taken from each patient's device. The first swab was immediately inoculated onto Blood Agar and MacConkey Agar plates to facilitate the isolation of a broad spectrum of aerobic and facultative anaerobic bacteria. The second swab was inoculated onto Sabouraud Dextrose Agar (SDA) heavily supplemented with chloramphenicol to suppress bacterial overgrowth and isolate fungal elements.

Bacterial cultures were incubated at 37°C for 24 to 48 hours and examined daily. Fungal cultures were incubated at a lower ambient temperature of 25°C and observed continuously for up to three weeks to account for slower-growing molds. Identification of bacterial isolates was systematically performed utilizing standard biochemical tests, including catalase, coagulase, and oxidase assays, followed by specific carbohydrate fermentation profiles. Fungal identification relied upon macroscopic colony morphology on the SDA plates and microscopic morphological examination using Lactophenol Cotton Blue (LPCB) tease mounts to carefully assess hyphal structures, conidiophores, and specific sporulation patterns.

Retrospective analysis of device failures

To evaluate the mechanical and electronic resilience of hearing aids in this climate, a comprehensive review of the departmental hearing aid dispensing and repair registry was conducted, encompassing a continuous three-year period from January 2019 to December 2021. While major device manufacturers routinely utilize accelerated environmental testing protocols such as continuous exposure to synthetic sweat and high heat to establish baseline durability and Ingress Protection (IP) ratings, this clinical analysis sought to capture genuine, real-world degradation rates and failure typologies.

Inclusion criteria for the retrospective analysis mandated that the devices were originally dispensed by the clinic (ensuring a known starting date), utilized daily by the patient, and brought in for formal functional assessment or repair due to mechanical or acoustic failure. Routine cleanings or standard tubing changes were not classified as device failures. To ensure rigorous and unbiased data extraction, the categorization of failures and the qualitative rating of physical degradation (such as the extent of battery terminal corrosion, the presence of visible moisture in the acoustic tubing, or transducer oxidation) was performed independently by two blinded clinical audiologists. Discrepancies in categorization were resolved through consensus.

Failures were classified into five primary domains:

Transducer malfunction

Total or partial failure of the receiver (speaker) or microphone, confirmed by electroacoustic analysis.

Power supply interface degradation

Significant corrosion, crystalline buildup, or mechanical fracture of the battery contacts or the battery door hinge.

Acoustic pathway occlusion

Severe, unyielding blockage of the sound bore, venting, or receiver port by hardened cerumen, crystallized salts, or dense fungal debris requiring laboratory removal.

Housing/shell integrity

Visible cracks, stress fractures, or chemical degradation of the Behind-The-Ear (BTE) casing or custom In-The-Ear (ITE) shell.

Circuit/DSP failure

Internal motherboard or digital signal processor failure that was not directly or visibly attributable to immediate moisture ingress upon gross inspection.

Statistical analysis

All extracted clinical and microbiological data were tabulated using standardized spreadsheet software and analyzed utilizing established biostatistical protocols. Descriptive statistics were utilized to report the frequencies, percentages, and central tendencies of device failure categories and specific microbial isolates. Continuous variables, such as the time elapsed to the first documented device failure, were expressed as mean values accompanied by their standard deviations (±SD). Categorical variables were rigorously assessed using the Pearson Chi-square test. Furthermore, differences in survival time (longevity) between various hearing aid form factors [e.g., standard BTE versus Receiver-In-Canal (RIC)] were evaluated using the Kaplan-Meier survival analysis method. A $p<0.05$ was considered to denote statistical significance across all tests.

RESULTS

Microbial colonization of earmolds

The cross-sectional microbiological swabbing of 150 active, chronically used earmolds revealed a profound and clinically concerning rate of microbial colonization. Pathogenic or opportunistic flora was successfully cultured from 117 individual earmolds, representing an overall microbial colonization rate of 78.0% (Figure 1).

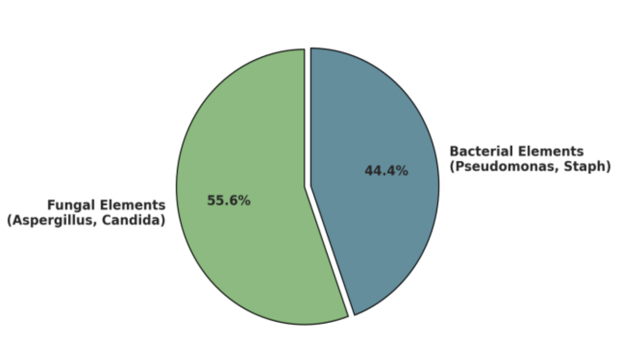

Figure 1: Distribution of fungal and bacterial isolates in colonized earmolds (n=117 positive cultures).

Fungal colonization was the dominant biological force in this damp, coastal climate, presenting in 55.6% (n=65) of the positive cultures. The identification process revealed a heavy preponderance of environmental molds. The most frequently isolated species was *A. niger*, accounting for 41.5% of the fungal load, followed closely by *A. flavus* at 24.6%. *C. albicans* was also present in 20.0% of the fungal cultures, highlighting a diverse mycological profile.

Bacterial growth was independently identified in 44.4% (n=52) of the positive cultures. The bacteriological profile was heavily dominated by recognized opportunistic pathogens known to thrive in the external auditory canal and cause acute clinical infections. *P. aeruginosa* was the most common bacterial isolate, found in 38.4% of the bacterial cultures. This was followed by coagulase-positive *S. aureus* (30.7%) and various strains of coagulase-negative *Staphylococci* (19.2%) (Table 1).

Table 1: Prevalence of microbial isolates in colonized earmolds, (n=117).

Microbial category	Specific isolate	Prevalence within category (%)
Fungal (55.6% of positive cultures; n=65)	*Aspergillus niger*	41.5
	Aspergillus flavus	24.6
	Candida albicans	20.0
Bacterial (44.4% of positive cultures; n=52)	*P. aeruginosa*	38.4
	Coagulase-positive *S. aureus*	30.7
	Coagulase-negative *Staphylococci*	19.2

*This table summarizes the microbiological survey of 150 active earmolds, which demonstrated an overall colonization rate of 78.0%.

Crucially, the study identified a high rate of complex, mixed biofilms. Co-infection featuring both distinct fungal and bacterial elements thriving on the same earmold was observed in 32 separate instances. Macroscopic evaluation of these heavily colonized earmolds prior to swabbing frequently revealed visible, deep-seated discoloration-often presenting as dark black or vivid green particulate matter firmly embedded within the microscopic pores of the silicone or acrylic matrices-which strongly correlated with positive, heavy culture results for *A. niger* and *P. aeruginosa*, respectively.

Device failure demographics and typology

The retrospective analysis yielded robust data on 412 distinct hearing aid repair events spanning the three-year observation period. The structural breakdown of the failed devices comprised standard BTE models (59.4%), modern RIC models (27.9%), and custom ITE/ITC models (12.7%). The mean age of the devices across all styles at the time of their first clinically logged failure was remarkably short, calculated at 18.4±6.2 months.

Upon categorizing the repair logs, transducer malfunction emerged as the overwhelming primary etiology for clinical intervention. Receiver/speaker failure accounted for the highest single proportion of repairs at 38.3% (n=158). This was followed closely by microphone degradation, which accounted for 29.1% (n=120) of the failures. Therefore, components directly responsible for acoustic transduction accounted for over two-thirds of all device mortality (Figure 2).

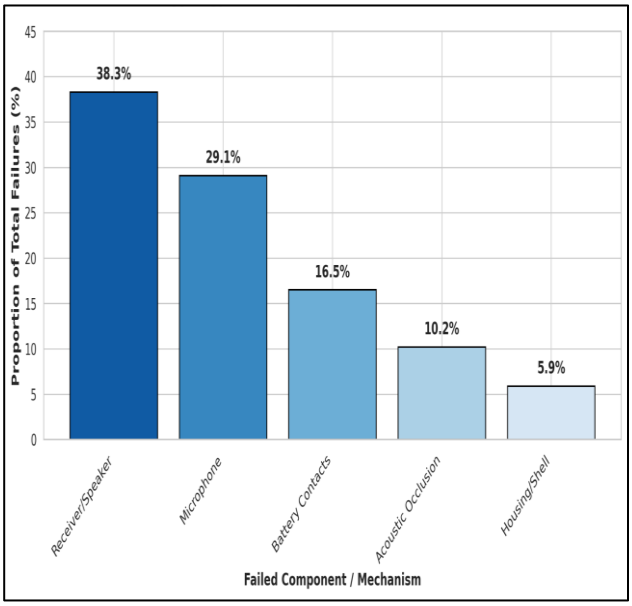

Figure 2: Typology of primary hearing aid component failures (n=412) over a three-year period in a coastal environment.

Battery contact corrosion, characterized by green or white oxidized scaling, was identified as the primary, critical failure mode in 16.5% (n=68) of the patient cohort. Acoustic pathway occlusion, resulting from an impenetrable composite of damp cerumen, crystallized atmospheric salt, and fungal hyphae, was responsible for 10.2% (n=42) of the clinical visits. Catastrophic shell and housing fractures accounted for the remaining minority of failures.

When stratifying failure rates and longevity by specific device style, a critical vulnerability was exposed. Modern RIC models demonstrated a significantly shorter mean time to first failure, failing at an average of 14.2±4.1 months. This was statistically significantly lower than the survival time of standard, traditional BTE models, which averaged 21.5±5.5 months (p=0.012).

DISCUSSION

The comprehensive data presented in this dual-arm study illustrates the severe, multifaceted, and deeply interconnected impact of a tropical monsoonal coastal climate on audiological rehabilitation. The findings unequivocally demonstrate that high atmospheric humidity and pervasive salinity act synergistically to rapidly degrade sophisticated microelectronics while simultaneously cultivating highly resistant, pathogenic biofilms. This reality necessitates a fundamental paradigm shift in how audiological care is prescribed, managed, and maintained in these specific geographic zones.

The extreme environmental impact on microelectronics

The significantly shorter lifespan of RIC devices-failing nearly seven months earlier on average than traditional BTE devices-highlights the specific, catastrophic vulnerability of placing acoustic transducers directly within the humid, occluded space of the external ear canal.[9] In a traditional BTE hearing aid, all delicate electronic components are housed behind the pinna, with only an inert hollow plastic tube entering the ear canal. In contrast, the RIC design suspends the delicate balanced armature receiver directly in the line of fire. The constant, daily exposure to elevated core body temperatures, volatile human sweat, and trapped ambient moisture easily bypasses standard external wax guards and nano-coatings. This leads to rapid internal oxidation, rust formation on the delicate transduction wires, and the deposition of crystalline atmospheric salt on the vibrating receiver diaphragms, ultimately freezing the mechanism.

Furthermore, the high incidence of battery contact corrosion (16.5%) underscores the chemical reality of atmospheric salinity. When warm, humid, salt-laden coastal air enters the hearing aid through the tiny seams of the battery door and subsequently cools against the metallic battery, microscopic condensation occurs. The presence of chloride ions in this condensation dramatically accelerates galvanic corrosion between the dissimilar metals found in the zinc-air battery and the internal gold or copper-plated contacts. This corrosion creates a high-resistance barrier, starving the DSP chip of adequate voltage and causing intermittent or total device shutdown.

To effectively mitigate this rapid degradation, audiology clinics in coastal areas must urgently transition away from traditional, passive chemical drying kits (silica gel). Clinical protocols must mandate the use of active, forced-air UV-C desiccation systems, which utilize gentle heat and circulating air, and have been proven significantly more efficacious in evaporating deeply trapped internal moisture and reducing residual microbial loads on the hardware.

Clinical considerations for earmolds, biofilms, and fitting

The staggering 78% microbial colonization rate indicates that in a tropical climate, an earmold rapidly transitions from being an inert acoustic conduit into a highly active, infectious fomite. The structural integrity, material choice, and physical fit of the earmold play a massive role in ear canal ventilation. A tightly fitting, unvented earmold completely abolishes the natural epithelial migration and aeration of the ear canal. Ensuring highly precise anatomical impressions and maximizing the diameter of acoustic venting can slightly reduce the trapped, stagnant moisture that fuels exponential biofilm growth.

The mycological dominance of *Aspergillus* species in this cohort perfectly mirrors the epidemiological profile of tropical otomycosis. The microscopic surface porosities of acrylic and silicone absorb moisture, providing an ideal, protected scaffold for fungal hyphae to anchor firmly. Once established, this fungal network traps exfoliated human keratin and cerumen, creating a nutrient-rich, impenetrable biofilm. The high prevalence of *P. aeruginosa* and *S. aureus* is equally alarming, as these are the primary causative agents of painful, acute diffuse otitis externa.[10]

Audiologists must vastly expand their standard patient counseling paradigms. Basic instructions regarding battery changes are wholly insufficient in the tropics. Counseling must include rigorous, daily equipment maintenance specific to high-humidity challenges, teaching patients how to visually inspect for early mold growth and how to properly utilize antimicrobial wipes safely on acoustic plastics.[11] When colonization inevitably leads to active clinical infection, a targeted medical approach to managing otitis externa is required. This must focus on immediate, frequent microscopic aural toilet by an otolaryngologist and the absolute, non-negotiable removal of the colonized audiological device until the canal epithelium has fully healed and the barrier function is restored.[12]

Broader implications, device survival, and patient psychosocial impact

The rapid, premature degradation of these expensive devices in coastal zones significantly alters the expected survival analysis of digital hearing aids, completely skewing the cost-to-benefit ratio for the patient. When devices fail prematurely-often just outside of the manufacturer's limited warranty period-patients are faced with exorbitant out-of-pocket repair costs. Consequently, the frequency of adverse events, ranging from minor physical discomfort due to structurally weakened, broken shells, to the psychological distress of complete, sudden acoustic failure, rises sharply.[13]

The profound psychological and functional impact of this high failure rate cannot be overstated. The neurocognitive experience of adapting to sensorineural hearing loss is already fraught with immense communication challenges, fatigue, and social withdrawal; the sudden, repeated loss of sound due to hardware failure aggressively interrupts central neural adaptation and destroys the patient's communicative confidence. In older, vulnerable adult populations, prolonged periods of hearing aid abandonment due to unrepairable devices have much broader systemic health implications. Unmanaged auditory deprivation in the elderly has strong, established correlations with accelerated cognitive decline, social isolation, and even increased rates of all-cause hospitalizations.

Ultimately, combating the highly unique clinical features and severe environmental risk factors of device degradation and chronic otomycosis in the tropics requires a fundamental, multidisciplinary shift. It demands advancements in materials science to create intrinsically antimicrobial polymers, a redesign of hearing aid architecture to better isolate microelectronics, and a complete overhaul of regional audiological care standards to prioritize aggressive moisture management.

CONCLUSION

High-humidity, monsoonal coastal climates dramatically and prematurely accelerate the catastrophic failure of sophisticated hearing aid microelectronics through deep moisture ingress and salt-induced galvanic corrosion, particularly affecting exposed acoustic transducers in modern RIC devices. Simultaneously, this aggressive environment promotes the extensive, rapid colonization of patient earmolds by highly opportunistic, pathogenic fungal and bacterial biofilms, dominated by *Aspergillus spp.* and *P. aeruginosa*. To ensure acceptable device longevity, protect the financial investment of the patient, and safeguard their ongoing otologic health, audiological protocols in tropical regions cannot rely on temperate-climate standards. They must urgently adopt aggressive active dehumidification technologies, heavily mandate stringent antimicrobial hygiene practices, and continuously advocate for moisture-resilient device architecture.

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