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TRENDS IN THE ADVANCEMENT OF MOBILE APPLICATIONS FOR THE DIAGNOSIS AND TREATMENT OF TINNITUS: A COMPREHENSIVE REVIEW OF SCIENTIFIC LITERATURE

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
G Funds collection

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Abstract

Introduction: Tinnitus is a condition that requires multidisciplinary care and monitoring. Widespread use of mobile devices and ready access to the internet offers a possible solution since smartphones can run apps programmed for a particular health problem. The aim of the article is to assess the scale and direction of how mobile apps are being created and used to diagnose and treat tinnitus.

Material and methods: Publications in Google Scholar, PubMed, and ResearchGate were searched for the years 2010–2023. The results of the review were organized by themes.

Results: Hits were organized into the following themes: (1) existing mobile apps for tinnitus, (2) apps supporting the diagnosis of tinnitus, (3) apps supporting tinnitus therapy, (4) a look to the future – sensors built-in or connected to mobile devices, wearables, artificial intelligence (AI), and big data systems.

Conclusions: Smartphone-based apps with ecological momentary assessment methods and the possibilities of using wearable diagnostic devices might be useful in better understanding the variability of tinnitus and perhaps its causes. Mobile crowdsensing and central databases with big data and artificial intelligence support appear to be a valuable resource for new scientific research. There are now mobile apps providing a variety of therapies – sound therapy, self-help psychology, and educational training. Equally important for tinnitus therapy are smart devices managed by mobile apps – hearing aids, cochlear implants, and other hearables. In the future, development of mobile technologies and artificial intelligence will help create smart therapy platforms for tinnitus.

Keywords: mobile apps • artificial intelligence • smartphone-based tinnitus treatment • smart devices • ecological momentary assessments

KIERUNKI ROZWOJU APLIKACJI MOBILNYCH W DIAGNOSTYCE I TERAPII SZUMÓW USZNYCH: PRZEGLĄD LITERATURY NAUKOWEJ

Streszczenie

Wstęp: Szumy uszne to schorzenie wymagające wielodyscyplinarnej opieki i monitorowania. Specjaliści poszukują w tym zakresie rozwiązań w coraz powszechniejszym dostępie do Internetu i coraz szerszym wykorzystaniu urządzeń mobilnych. Co więcej, smartfony posiadają ekosystem aplikacji, który można rozszerzyć o nowe aplikacje zaprogramowane pod kątem konkretnego problemu zdrowotnego. Celem pracy była ocena skali oraz kierunku tworzenia i wykorzystania aplikacji mobilnych do diagnostyki i leczenia szumów usznych.

Materiał i metody: Przeszukano publikacje w Google Scholar, PubMed i ResearchGate z okresu 13 lat (2010–2023). Wyniki przeglądu uporządkowano tematycznie.

Wyniki: Rezultaty uporządkowano w następujące kategorie tematyczne: 1) aplikacje mobilne w kontekście szumów usznych obecne w przestrzeni internetowej; 2) aplikacje wspomagające diagnostykę szumów usznych; 3) aplikacje wspomagające terapię szumów usznych; 4) spojrzenie w przyszłość – czujniki wbudowane w urządzenia mobilne lub z nimi połączone, przenośne urządzenia diagnostyczne, sztuczna inteligencja (AI), systemy gromadzenia dużej ilości danych.

Wnioski: Aplikacje na smartfony z krótkimi chwilowymi ocenami w czasie rzeczywistym i możliwością wykorzystania przenośnych urządzeń diagnostycznych mogą być pomocne w lepszym zrozumieniu zmienności szumów usznych oraz ich etiologii. Gromadzenie dużej ilości danych od użytkowników urządzeń mobilnych oraz ich analizowanie ze wsparciem sztucznej inteligencji to cenne źródło rozwoju badań naukowych. Pojawiają się nowe projekty aplikacji mobilnych prezentujące różnorodną ofertę terapeutyczną – terapię dźwiękiem, samopomoc psychologiczną i treningi edukacyjne. W terapii szumów usznych równie ważne mogą okazać się inteligentne urządzenia zarządzane przez aplikacje mobilne, takie jak: aparaty słuchowe, implanty ślimakowe, wielofunkcyjne smart słuchawki. Rozwój technologii mobilnych i sztucznej inteligencji niewątpliwie przyczyni się w przyszłości do stworzenia inteligentnych platform terapii szumów usznych.

Słowa kluczowe: aplikacje mobilne • sztuczna inteligencja • leczenie szumów usznych oparte na smartfonie • inteligentne urządzenia • ekologiczne oceny chwilowe

Key to abbreviations	
AI	artificial intelligence
AIS	*Athens Insomnia Scale*
CBT	cognitive-behavioral therapy
CI	cochlear implant
conv-TRT	conventional TRT
EEG	electroencephalographic
EMA	ecological momentary assessment
EMAI	ecological momentary assessment and intervention
EMI	ecological momentary intervention
FTRS	Fudan Tinnitus Relieving System
GAD-7	*Generalized Anxiety Disorder 7-item*
GGTI	GGTinnitus app
HADS	*Hospital Anxiety and Depression Scale*
HAs	hearing aids
H-THI	*Tinnitus Handicap Inventory – Hebrew*
JITAIs	just-in-time adaptive interventions
MARS	*Mobile Application Rating Scale*
MCS	mobile crowdsensing
mHealth	mobile health
ML	machine learning
NFB	neurofeedback
PSS	*Perceived Stress Scale*
PSQI	*Pittsburgh Sleep Quality Index*
PTM	progressive tinnitus management
RL	reinforcement learning
smart-TRT	smart device-based Tinnitus Retraining Therapy
TFI	*Tinnitus Functional Index*
THI	*Tinnitus Handicap Inventory*
TQ	*Tinnitus Questionnaire*
TRT	Tinnitus Retraining Therapy
TYT	TrackYourTinnitus (mobile platform)
VAS	*Visual Analogue Scale*

Introduction

Subjective tinnitus is the conscious awareness of a tonal or composite noise for which there is no identifiable corresponding external acoustic source [1]. Tinnitus is considered acute if the patient has experienced it for less than 3 months, sub-acute after 3 months, and chronic if the patient has experienced it for 6 months or more [2]. Tinnitus is not a disease, but a symptom that may occur in the course of various diseases and conditions [3]. Subjective tinnitus may result from pathological neural activity at different levels of the auditory pathway, although the underlying pathology is still not understood [4]. Based on epidemiological studies, tinnitus affects approximately 10–15% of the American population, of which 20% of them consider it a significant problem [5–7]. Research conducted at the Institute of Physiology and Pathology of Hearing, Poland, in 1999–2000 showed that tinnitus is experienced by approximately 20% of Poles over 18 years of age, and 4.8% reported the presence of permanent tinnitus [8].

Tinnitus usually does not pose a threat to the patient, but it can significantly worsen their quality of life and correlates positively with levels of depression, anxiety, and sleep disorders [9–12]. Patients often report variations in tinnitus loudness and severity depending on a range of factors [13–15].

Current recommendations regarding the diagnosis and treatment of patients with tinnitus are included in the following American and European documents: *Clinical Practice Guideline: Tinnitus Executive Summary* from 2014 [16]; *A Multidisciplinary European Guideline for Tinnitus: Diagnostics, assessment, and treatment* from 2019 [2]; and *Tinnitus: Assessment and Management* from 2020 [17]. These reports emphasize the multifactorial nature of tinnitus and the need for a multidisciplinary team for diagnosis and treatment of the condition. According to the above documents, cognitive-behavioral therapy (CBT) is, so far, the best documented scientific method for treating the condition. Hearing aids are recommended for patients with tinnitus who have hearing loss, and improving hearing is an important factor in reducing the severity of tinnitus. The guidelines also refer to neurostimulation methods, which are safe but have not yet been recommended due to the small number of reliable scientific

Table 1. Thematic categories and search criteria in the title/abstract of articles

Thematic categories	Search criteria in the content of the title/abstract
Existing mobile apps for tinnitus available on the internet	mobile/smartphone apps – tinnitus – review mobile/smartphone apps – tinnitus – identification mobile/smartphone apps – tinnitus – analysis – evaluation
Mobile apps supporting diagnosis of tinnitus	mobile/smartphone apps – tinnitus – diagnosis mobile apps – device – tinnitus – diagnosis – validation mobile/smartphone apps – tinnitus – hearing – assessment mobile/smartphone apps – tinnitus – self management
Mobile apps supporting tinnitus therapy	mobile/smartphone apps – device – tinnitus – therapy – treatment mobile/smartphone apps – tinnitus – sound therapy mobile apps – tinnitus – CBT therapy mobile/smartphone apps – tinnitus – self-help –management
A look to the future	mobile/smartphone apps – tinnitus – digital technologies tinnitus – artificial intelligence – machine learning tinnitus – smart therapy mobile health – tinnitus – sensors mobile health – mental health – CBT therapy

studies confirming their effectiveness, and sound therapy methods that are widespread and considered safe, but again cannot be recommended due to the small number of high-quality clinical trials. None of the guidelines recommend drug treatment.

An ongoing goal of research and clinical work is to examine in more detail the factors or ailments that aggravate tinnitus and find ways of better coping with the condition in everyday life [18]. Ways are also being sought to cut waiting times and improve access to reference centers who are called on to provide multidisciplinary diagnostics and therapy. A solution to these problems may be new technologies and rapidly developing mobile networks. Attention is focused on smartphones, which have increasing worldwide reach and more advanced capabilities. Importantly, smartphones have an application (or app) ecosystem into which new apps designed to deal with particular health problems can be loaded.

The use of mobile apps in the health field is constantly expanding into areas of diagnosis and medical interventions. Mobile apps are used for mental health, enabling wide access to therapies that are particularly effective in dealing with depression and anxiety [19]; they can also be used, with the support of AI, to develop rapid and effective screening diagnostic methods for diseases such as cancer [20].

The outbreak of COVID-19 has led to a recognition of the great potential of mobile apps, since rapid, cheap, and easily accessible diagnosis of infection was essential in controlling the disease. Mobile apps and AI techniques were used to identify COVID-19 patients based on a variety of clinical, geographic, demographic, radiological, serological, and laboratory data. In a future pandemic, mobile apps will no doubt play a critical role in rapidly diagnosing infection based on image data and clinical symptoms [21].

The aim of the present study was to assess the scale and direction in which mobile apps are being created and used to diagnose and treat tinnitus, based on a review of the available scientific literature.

Material and methods

Publications in Google Scholar, PubMed, and ResearchGate published in the period 2010–2023 were searched. Thematic categories and search criteria in the content of titles and abstracts are presented in **Table 1**.

Results

Existing mobile apps for tinnitus

An up-to-date overview of existing apps on iOS and Android platforms which can support the management of tinnitus has been presented by Mehdi et al. [22]. The authors identified and described 64 apps categorized into six groups. (1) Tinnitus relief (14 apps) – techniques like masking sounds, relaxing sounds, notched sounds, and acoustic neuromodulation. (2) Cognitive Behavioral Therapy or CBT (10 apps) – mostly not directly related to tinnitus, but dealing with depression, anxiety, and stress which are common psychological comorbidities accompanying tinnitus. (3) Hearing protection (8 apps) – measuring the noise level in the environment or music volume and inform the user about dangerous sound levels, which is important in preventing hearing deterioration and intensification of tinnitus. (4) Hearing testing (11 apps) – testing hearing at different frequencies and in noisy environments; testing the hearing level of children using visual and auditory tasks. (5) Hearing enhancement (10 apps) – amplifying individual sounds based on hearing tests, cutting out ambient noise, supporting auditory attention exercises. (6) Smartphone-based mobile EEG (electroencephalographic) systems (11 apps) – to study real-time brain activity, designed in combination with a handy and mobile dry EEG headset or semi-dry EEG cap; these apps were included in the context of tinnitus because of previous research showing that tinnitus has its own neural correlates. In addition, one of the more popular methods in the alternative treatment of tinnitus is neurofeedback (NFB) – a non-invasive method, generally based on real-time EEG recording, which is presented visually to the patient as positive or negative feedback during training.

Different app rankings have been presented by Mehdi and colleagues in another article [23]. The authors identified 34 apps on iOS and Android platforms, of which 24 were used for tinnitus therapy – the vast majority of them were sound therapy applications which used various sounds – masking, broadband, relaxation, and neuromodulation (with appropriate frequency bands). There were 10 CBT apps, the majority of which were not aimed directly at tinnitus but were helpful in dealing with depression, anxiety, and stress. Among them were three chatbots – conversational agents based on artificial intelligence (AI), whose conversations and advice are based on CBT theory or positive psychology. The average MARS (*Mobile Application Rating Scale*) results calculated on the basis of the mean of four categories (engagement, functionality, aesthetics, and information quality) were assessed on a 5-point scale (1, inadequate to 5, excellent) and ranged from 2.65 to 4.60. These ratings indicate that there were no low-quality apps; all were rated between medium and high quality. However, only 7 of them were backed by clinical research – TinnitusTherapy (Lite), ReSound Relief, SimplyNoise, and Audio Notch as sound therapy apps, and Wysa, Woebot, and MindShift as CBT chatbots [24]. Existing clinical studies on the effectiveness of tinnitus therapy apps have also been described by Nagaraj and Prabhu [25].

The above demonstrates that there are functional and user-friendly mobile apps aimed at dealing with tinnitus, mainly in the field of sound training. Additionally, clinicians and researchers see an increasing need for reliable scientific verification of their clinical usefulness. The scope of tinnitus therapy can be expanded by developing mobile apps with broader therapeutic and diagnostic reach, e.g. in terms of diagnosis, protection, and enhancement of hearing.

Wide access to functional and valuable mobile apps has been confirmed by Deshpande and Shimunova [26]. The authors described the functionality and availability of apps for tinnitus which were available on iOS, Android, and Windows. Both free and paid apps are available on each platform, with a smaller percentage of free apps occurring on iOS (53%) compared to Android (86%) and Windows (85%). Only 8% of apps were available on multiple platforms. A cost-feature analysis revealed that the more expensive apps did not necessarily offer more features. The Android platform had the most tinnitus apps. Among the educational, diagnostic, and therapeutic categories, therapeutic apps dominated, with sound apps predominating both in terms of number and variety of functions. A small proportion of 'misinformation' apps (home remedies, supplements, medically inappropriate strategies) were detected across platforms (5% Android, 3% iOS, 0% Windows).

In 2016, Sereda et al. [27] performed a web survey on 643 respondents suffering from tinnitus in order to examine the extent of use, motivation, and usefulness of mobile apps for tinnitus. The majority of respondents (75%) had never used an app for management of tinnitus, mainly because of lack of awareness of their availability, with 20% saying the reason was that they were not good with technology. These data are from 2016 and the figures will no doubt have changed. In recent years, the level of use of mobile apps by tinnitus patients, their availability and attractiveness, as well as the familiarity with new technology, which is increasingly intuitive, has been growing. The authors noted that in 70% of the apps, sound was the main focus. Other components included relaxation, CBT (dealing with stress and depression), meditation and mindfulness, information and education, hypnosis, and assessment of tinnitus. The authors presented a list of 55 apps that people used for tinnitus (14 of which were developed specifically for the condition). Quality assessment of the 18 most popular apps using MARS resulted in mean scores ranging from 1.6 to 4.2 (out of 5).

Kutyba et al. [28] identified and described 16 sound apps available in the Google Play Store which had the ability to generate different acoustic signals, were free of charge, and were in Polish. Most of them were for relaxation, meditation, and sleep, and only one (ReSound Tinnitus Relief) was specifically designed for people suffering tinnitus. In addition to standard functions such as a sound library, timer, and sound mixer, ReSound Tinnitus Relief includes a set of relaxation exercises and information on tinnitus and available therapies. Kutyba pointed out that all the apps may be useful to a patient as a complement to therapy given by a specialist. Here, it is worth considering the development of understandable instructions for patients with tinnitus on how to use therapeutic and relaxation sounds on a mobile app.

Mobile apps supporting diagnosis of tinnitus

In the area of tinnitus diagnosis using mobile apps, two major directions are apparent. The first relates to self-measurement, i.e. diagnostic assessment of tinnitus or hearing level performed by the patient themself. The second direction is the use of EMA-MCS platforms (mobile crowdsensing platforms based on ecological momentary assessment), which allow tinnitus variability and its accompanying factors to be recorded in real time thanks to self-reporting and automatic data collection using a sensor, smartphone, and app. The data is collected in a central database for research purposes.

Chamoso et al. [29] and Vittorini et al. [30] describe the design of a device and an app for self-measurement of tinnitus using pure-tone audiometry, acuphenometry, and tinnitus severity assessment via questionnaires: the *Pittsburgh Sleep Quality Index* (PSQI), *Khalfa Hyperacusis Questionnaire*, and *Tinnitus Handicap Inventory*. The project consists of a simple electronic device that generates pure tones combined with a headset and bone conduction transducer linked to a mobile app that manages the testing and provides the results. The app gives an assessment of the level of hearing and type of hearing loss, questionnaire results, and tinnitus characteristics. The authors describe the usability tests and improvements made to the tool, as well as the first validity tests, which showed that 25/25 of the app's audiometric test reports were consistent with a standard test performed by a technician.

One step in diagnosing tinnitus involves the diagnosis of hearing level. There are increasing numbers of apps that perform stand-alone hearing tests, most often used for screening or as a way of complementing a standard test. In order for apps to replace the standard examination and provide effective hearing monitoring outside the clinic (which will enable “just in time” medical intervention), certain conditions must be met, which are described by Handzel and Franck [31]: they include bone and air conduction tests, understanding speech in noise, quiet environment, appropriate masking of the other ear, calibrated headphones, and appropriate sampling (limiting distractions). In mobile diagnostics, this is a developing topic that has the potential to confer many benefits to users and health services.

As previously mentioned, an important issue in the diagnosis of tinnitus as a variable and multifactorial ailment is EMA (ecological momentary assessment) [32,33]. EMA is a real-time measurement of conditions, factors, and symptoms through the use of many short, repeatable assessments, minimizing retrospective bias. Henry et al. [34] and Wilson et al. [35] describe the design of EMA in diagnosing tinnitus using various technological solutions. In Germany, a non-commercial mobile platform called TYT was developed, which serves as the EMA's mobile crowdsensing platform (EMA-MCS), thanks to the collaboration between the Tinnitus Research Initiative and the Institute for Databases and Information Systems at the University of Ulm. Data is collected in a central database, which enables the collection of a large amount of data for research analysis. With real-time research, the dynamics of tinnitus variability can be examined, looking at how the variability depends on various factors (psychological, behavioral, environmental) and allowing a more accurate assessment of their impact to be made than in a retrospective study [36,37]. In preliminary studies, research has indicated that regular use of EMA has no effect on tinnitus annoyance [34,36]. Data in TYT is collected in three ways [36–38]: (1) through registration questionnaires describing the user and their difficulties with tinnitus; (2) through EMA questionnaires containing eight questions completed up to a dozen times a day via set notifications – completing them takes about a minute and relates to various psychological and behavioral dimensions (e.g. stress level, concentration, tinnitus perception, arousal, mood); EMA requires a short, easy assessment, e.g. with the help of a VAS (visual analogue scale) [39]; (3) by acoustic measurement of ambient sounds via the phone's built-in microphone – a future-proof element that makes it possible (although not yet used) to automatically collect various data (environmental, behavioral, physiological) via built-in sensors and connect wearable diagnostic devices or biosensors.

The reference architecture of the TYT platform is described by Pryss et al. [40] and Kraft et al. [41] who also outline its technological development and data management. The TYT platform can deposit anonymized data in a central database, give user feedback, and give results to treating physicians. Based on TYT data, several studies have emerged about the effect of emotional states and their dynamics on the perception and severity of tinnitus [13], and how the variability of tinnitus depends on time-of-day [14]. Research has also confirmed the value of a prospective study [15], from which it is apparent that (1) the variability of tinnitus tested prospectively using EMA was noticed even in those people who did not notice it retrospectively; and (2) the level of stress correlated positively with the severity of tinnitus in the EMA test, even in those people who did not notice the relationship retrospectively. First predictions using machine learning on a large amounts of data from TYT have been described by Breitmayer et al. [42], Allagier et al. [43], and Pryss et al. [44]. Notably, Breitmayer found, based on a data set of 45,935 responses and using different machine learning techniques, that the presence of tinnitus could be predicted with an accuracy of up to 78%, with an area under the curve as high as 85.7%.

The above research indicates the possibility of widening the availability of diagnostics by using efficient self-measurement methods. It also indicates how new diagnostic and predictive models of tinnitus and comorbidities can be created by collecting and analyzing large amounts of data using EMA, MCS, and AI techniques.

Mobile apps supporting tinnitus therapy

The previous section on identifying mobile apps for tinnitus found that there was a clear dominance of apps offering sound therapy in various forms. The main motivation for using such apps was to use sounds to mask tinnitus, to relax, and to fall asleep more easily. Clinicians are now discovering the possibilities of also using mobile apps for more complicated sound therapies, such as acoustic coordinated reset neuromodulation therapy for tinnitus. Hauptmann et al. [45] presented an experimental system based on a mobile app that supports manual and adaptive tinnitus pitch and loudness matching, creation of therapy signals, transfer of the signals to a mobile device, programming the mobile device, recording of patient responses, and presentation of outcome measures. The authors confirm that mobile devices are able to reliably and accurately deliver acoustic therapy signals. For therapy, a mobile device can be operated independently and effectively by the patient after a short initial training. Even though the patient operates independently, the treating physician can constantly monitor how therapy is progressing: therapy compliance is documented within the mobile device and transferred to the clinician's computer, where the clinician can analyze and solve emerging difficulties.

Beyond using sound therapy, it has also been noted that users are seeking additional forms of support in managing tinnitus. Apps have begun to appear that supplement sound therapy with additional elements such as education and psychological training.

Evaluation of the effectiveness of tinnitus sound therapy apps, alone or in combination with other elements, are presented in **Table 2**. This work largely confirms that mobile apps can be an effective tool to reduce the severity of tinnitus while being cost-effective and easy to access. However there is still a need for the efficacy of these apps to be explored in large randomized controlled clinical trials.

An example of a mobile application that is CE marked and was placed on the market as a medical device in 2019 in German language is Kalmeda Tinnitus app. The app consists of 5 levels with nine steps each. Levels 1 and 2 of the behavioral therapy (areas redirecting attention, relaxation) are typically completed in 3 months. Subsequent

Table 2. Evaluation of the effectiveness of tinnitus sound therapy apps, alone or in combination with other elements, based on selected research

Study	Rehabilitation strategy	Population	Outcome measures	Efficacy of rehabilitation strategy
Kim et al. [46]	Smartphone app, delivering notched music therapy for 30–60 min per day in a quiet environment and ginko combined treatment for 3 months. Duration and frequency of app usage were saved on the server and could be checked by the physician.	individuals with chronic tinnitus ($n = 26$)	1. THI 2. VAS – perceived tinnitus loudness, noticeable time, annoyance, effect on daily life.	THI scores improved significantly ($p = 0.03$) after treatment, especially emotional component.
Tyler et al. [47]	Sound therapy provided by the ReSound Relief app for CI patients. Sounds were streamed from an iPod to the CI using a Cochlear Wireless Mini Microphone 2+. Laboratory trial: matching the sound, listening to it for 5 min, assessing the effectiveness and acceptance level of the sounds. Home trial: listening to selected sounds at home for 2 weeks.	CI (Nucleus 6 processor) users with tinnitus: laboratory trial, $n = 13$; home trial, $n = 10$	Laboratory trial on a scale of 0–100: – tinnitus loudness – annoyance of the tinnitus – sound acceptability Home trial on a scale of 0–100: – tinnitus loudness – overall effectiveness of sound therapy.	Laboratory trial: all 13 participants had lower ratings for tinnitus loudness. Home trial: the overall effectiveness of sound therapy 3 of 10 rated 70% or higher, 6 of 10 from 30% or higher.
Sabarish, Kurthika [48]	Sound therapy provided by the Tinnitus Therapy Lite app for 45 min a day for 1 month without changing previously made settings (sound and volume selection). Regular follow-up of usage done every 5 days.	individuals with tinnitus ($n = 5$): 4 with hearing normal and 1 with bilateral mild sensorineural hearing loss	THI	There was a decline of at least 18 points in THI scores for all participants.
Kutyba et al. [49]	Sound therapy provided by the ReSound Tinnitus Relief app for at least 30 min a day for 6 months: self-selected sound, quieter than your own tinnitus, used in a silent environment, before bedtime or when tinnitus disrupted daily tasks.	individuals with chronic tinnitus ($n = 52$)	1. TFI 2. THI 3. App usage assessment survey (after 3 and 6 months from starting sound therapy).	Clinically significant improvement declared: – after 3 months 11.5% of users (THI), 27% (TFI) – after 6 months 53.8% of users (THI), 58% (TFI). App easy to use – 86.4%. Liked to use the app daily – 73%.
Abouzari et al. [50]	Tinnitus-specific CBT and personalized and frequency-matched sound therapy provided by the app for 8 weeks: 2 h daily listening to the sound and 2–3 h weekly on CBT modules.	individuals with chronic, constant bilateral, non-pulsatile tinnitus ($n = 30$): 20 in treatment group and 10 in control group (waitlisted)	1. THI 2. GAD-7 3. PSS	The two cohorts had similar changes in GAD-7 ($p = 0.07$) and PSS ($p = 0.34$). The treatment group had a significantly higher improvement in THI scores (17.2 vs 5.3, $p = 0.04$).
Tang et al. [51,52]	Using FTRS app, patients were recommended to listen to tailor-made music for > 2 h a day (with headphones or speaker) and fill in self-help questionnaires on the app at baseline, after 1 month, and after 2 months of treatment. FTRS provides a large amount of data for clinical research.	users of the FTRS app: $n = 2744$ at baseline $n = 54$ at 2-month follow-up	1. THI 2. HADS 3. AIS	The scores of THI (51.5–33.8), HADS-A (6.93–4.56), HADS-D (6.38–3.78), and AIS (7.65–5.92) were significantly improved at 3-month follow-up compared with baseline. There were significant negative correlations between the scores and follow-up time for THI.

Table 2 continued. Evaluation of the effectiveness of tinnitus sound therapy apps, alone or in combination with other elements, based on selected research

Study	Rehabilitation strategy	Population	Outcome measures	Efficacy of rehabilitation strategy
Engelke et al. [53]	Structured counseling combined with sound therapy provided by the app in two phases: – baseline phase (tinnitus symptoms were measured daily (min 7 days) using app-based EMA using 10 VAS questions; – intervention phase: 12 weeks of daily sessions of structured counseling, sound therapy (at least 15 min per day) and EMA.	individuals with chronic tinnitus indicating at least a mild tinnitus handicap ($n = 21$)	1. THI 2. EMA module via app – 10 VAS questions – an end-of-day diary to track changes in tinnitus symptoms evoked by the intervention. A randomized multiple-baseline design across groups was used.	The mean THI was improved by 11.8 points ($p < 0.001$). 72% of patients had meaningful clinically improved THI scores (THI ≥ 7). Positive relationship between tinnitus distress and loudness weakened over the course of the study.
Suh et al. [54]	Smart-TRT was compared with conv-TRT. Smart-TRT: directive education; 3 interactive smart pad applications (numerous video clips, 1 a month) and sound therapy (white noise via smartphone at least 6 h a day). Conv-TRT: 3 sessions of counseling (1 a month) provided by a single clinician and sound therapy.	individuals with chronic tinnitus ($n = 84$): 42 in smart-TRT group and 42 in conv-TRT group	1. THI 2. Four VAS questions (awareness of tinnitus, annoyance, loudness of tinnitus, effect on daily life)	In both groups THI scores improved significantly over time ($p < 0.001$). There was no difference between the groups ($p = 0.76$). In both groups the VAS scores improved significantly over time in awareness, annoyance, effect on daily life.

levels 3–5 deal with the areas of mindfulness, acceptance, self-efficacy and are typically completed in not less than 7 months. Exercises are complemented by soothing nature and background sounds, guided meditation, and tinnitus related information [55]. Walter et al. [55] tested its safety and effectiveness in 187 patients with tinnitus in a randomized controlled trial. Tinnitus related distress and associated burdens (depression, stress) was significantly decreased in the intervention group compared to the control group. The results indicated significant reductions of TQ (*Tinnitus Questionnaire*) sum score in intervention group: -13.36 ± 1.00 compared to control group: -0.63 ± 0.98; $p < 0.0001$.

An interesting therapeutic project using a mobile app was presented by Henry et al. [56]. The authors developed and tested the Tinnitus Coach mobile app, which supports learning and creating individual coping strategies based on PTM (progressive tinnitus management). Users were given access to various functions, e.g. the opportunity to independently identify problematic situations and create coping strategies for it (Add & Use Plans); they also had access to quick sources of help in the form of sounds and relaxation trainings (Sampler) and short articles on topics related to tinnitus in general, as well as to the coping skills offered by the app (Learning Nook). Henry and colleagues found that users were more likely to use ready-made solutions prepared in the app than tasks requiring the self-creation of coping strategies.

Other projects of tinnitus education and psychological therapy via smartphone apps have recently appeared which involve working with the app using intuitive and simple tasks [57,58]. The first, by Schlee, developed and explored the feasibility of an educational training app (Tinnitus Tipps App) containing 108 self-help tips given every day for 4 months. Based on their research, the authors pointed out that frequent and intensive use of the app is crucial for treatment success – participants that used the app more often and interacted with it intensively had a stronger improvement in tinnitus. The second, by Oron, was an open pilot trial of the effectiveness of the GGTinnitus app (GGTI), a CBT-based program of 48 levels of short quests that aim to change maladaptive, catastrophic beliefs. Participants are asked to train for a few minutes daily, preferably before sleep, in order to consolidate memory and are advised to complete the tasks in 16 days. Of the 14 participants taking part, only 2 did not experience any reduction in H-THI (*Tinnitus Handicap Inventory – Hebrew*) score.

In terms of projects that are encouraging, pleasant, and encourage independent therapy for tinnitus, the "serious game" concept described by Schrickler [59] is interesting. It is an idea for a virtual game that in the context of tinnitus aims to suppress irrelevant sounds by focusing on target sounds and ignoring the background. Specifically, the user must detect target animal sounds from a background, e.g. similar to sounds on a farm or similar to their own tinnitus. Compared to traditional hearing training, its advantages are that it can be played at any time, is enjoyable, provides immediate feedback, and can be steadily increased in level of difficulty, raising motivation and learning.

Demoen et al. [60] have described an approach where the mobile app does not completely replace the therapeutic program, but complements and continues it, an approach that may reduce treatment costs. The protocol they describe is for a randomised controlled trial which aims to gauge both the effectiveness and cost of a mixed physiotherapy and counseling program for somatic tinnitus using an app. The experimental group receive the blended physiotherapy program comprising six in-clinic physiotherapy sessions over a period of 12 weeks (1 every 2 weeks) as well as an exercise and counselling program provided by an app. The control group receive the standard care program comprising 12 weekly in-clinic physiotherapy sessions.

An example of using a chatbot within a mobile app has been presented by Bardy at al. [61]. The authors performed a randomized, 2 parallel-group trial to compare the clinical effectiveness of iCBT delivered only through a chatbot mobile app (Tinnibot) and iCBT delivered through a Tinnibot together with telepsychology (with the assistance of a video-psychoeducational psychologist). The intervention period was 8 weeks, with assessments at pre-intervention, post-intervention, and 2 months follow-up. The study showed that, 16 weeks after the start of the iCBT program, over 60% of participants in both groups (Tinnibot only or hybrid intervention with telepsychology), showed a clinically significant decrease in tinnitus distress. The addition of telepsychology might be beneficial, but not essential for the effectiveness of the treatment. Tinnibot incorporates traditional CBT practices of identifying and challenging negative thoughts, activating behavior, training in relaxation, mindfulness, acceptance, and gratitude, and creating environments containing relaxing sounds.

An important factor in the use of mobile apps for self-help is the user's motivation – to complete the proposed therapy and make the most of what the app offers and to regularly feed in data that helps with research and therapeutic outcomes. The studies mentioned earlier indicate that there is quite a high percentage of test subjects who disqualify themselves at an early stage of the study due to failure to complete the therapy, technical difficulties, omission of complete answers, or losing contact [49,51,57,58]. At the same time, researchers often emphasize the relationship between the effectiveness of therapy and the frequency and time spent on it [49,51,57]. There is therefore a need for further research into factors that will make an app's functions more attractive and intuitive so that the user is more motivated to use it. Clinicians can play an important role here by helping to match an app's features to the patient's needs and by monitoring the course of therapy. We think that specialists dealing with the diagnosis and treatment of tinnitus should familiarize themselves with what apps exist, as well as their functions and effectiveness, so that appropriate solutions can be proposed to their patients.

A look to the future

Searchfield et al. [62] describe four generations of technological and digital development of tinnitus therapy, with the fourth the current generation of AI, hearables, biosensors, and wearable technology.

AI in mHealth means analyzing and learning from huge amounts of data through ML (machine learning) and RL (reinforcement learning) to create new diagnostic paths, new models, and profiles of different health ailments [18]. The review by Milne-Ives et al. [63] shows the diversity and feasibility of using AI to support mobile apps for mental health in a variety of ways, e.g. for prediction of mood and stress, for natural language conversations, and for delivery of notifications. The importance of AI is also emphasized in optimization of just-in-time adaptive interventions (JITAIs) and ecological momentary interventions (EMIs) – personalized interventions in a person's daily life, given at the right time, based on real-time assessment. In this way, JITAI adapts contextually to the changing internal state of the individual [63–67]. The distinguishing feature of JITAI compared to EMI is the use of statistical methods to improve and tailor interventions over time for a given individual [66]. The development of EMI and JITAI, based on mobile data collection technologies (e.g. sensors, wearables, powerful computational capabilities of smartphone), is currently accelerating in the area of mHealth, including psychotherapy and behavioral approaches to dealing with depression, anxiety, stress, and addictions [65–67]. Designed interventions may involve both the delivery of interventions automatically via a mobile app and delivery of just-in-time support by the doctor/therapist based on data provided by the app [66]. Intervention content can be delivered in various ways – as notifications, text messages describing tasks to be performed, visual and audio images, conversational interventions (chatbots), and activation of a support network [66]. Algorithms can be included that change the settings of a therapeutic device, e.g. hearing aid, cochlear implant, sound generator, depending on the stream of delivered data.

The possibilities of using ML algorithms are increasing in the field of medicine. Manta et al. [68] described a study using ML for tinnitus diagnosis based on wavelet-transformed auditory evoked potential signals and clinical data. The first mentions of using ML on large amounts of data from TYT can be found in Breitmayer et al. [42], Allagier [43], and Pryss [44]. Interesting developments have been presented by Doborjeh et al. [69], where the authors demonstrated the potential use of AI algorithms to predict tinnitus therapy outcomes based on EEG data. Neural networks were used to model frequency features of the EEG and functional connectivities, giving up to 99% accuracy for predicting whether patients would be responders or non-responders to sound-based therapy. The authors point out that this is the first step towards creating a real-time prognostic digital health system based on a small number of EEG variables from a wearable device that a patient could use at home.

Another possibility for use of AI in mobile apps are chatbots. Chatbots are conversational guides/therapists based on AI that could be used in medicine and psychology to analyze patient data in a real time and suggest relevant solutions. Assessments of their effectiveness was described by Moulya and Praghathi [70], Karkosz et al. [71], Klos et al. [72], Pryss et al. [73], Gutu et al. [74], and Fulmer et al. [75]. Chatbots in a therapeutic mobile app could be used as guides, verbally suggesting certain steps or solutions, or they could recognize emotions, verify the user's current needs, or propose, in a conversational form, specific therapies (such as CBT, motivational dialogue, positive psychology, etc.).

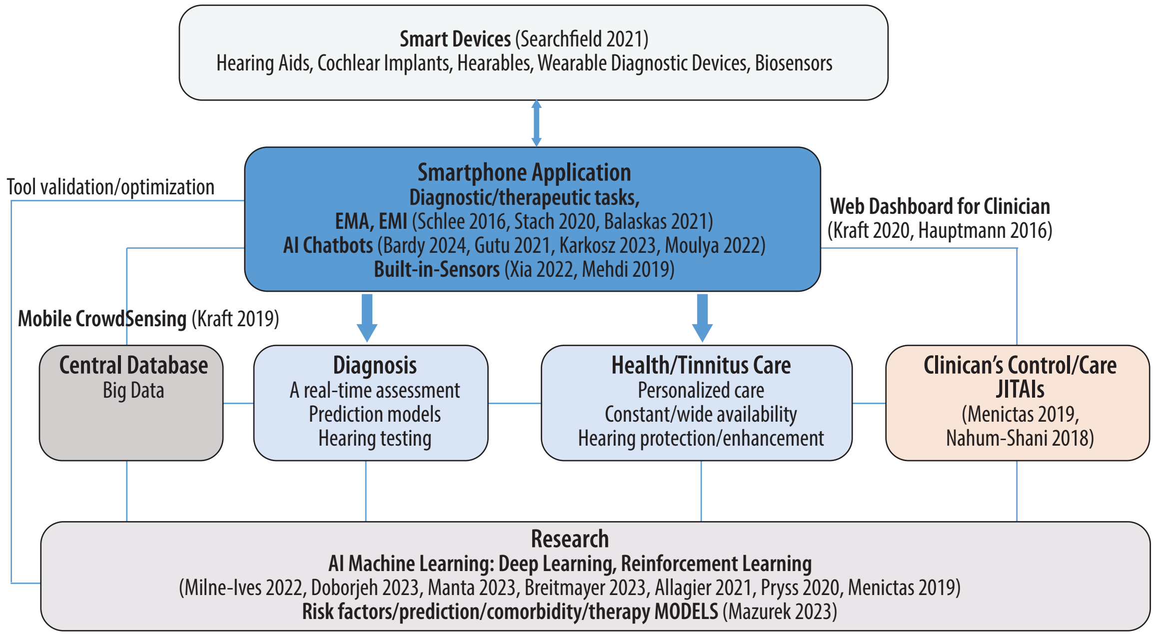

Figure 1. Directions and technological background in the development of smartphone apps for tinnitus diagnosis and treatment

The increasing prevalence of smart mobile devices and apps enables the combined use of mobile crowd sensing (MCS) and ecological momentary assessments (EMAs) in the healthcare domain. Moreover, the combined use of MCS and EMA increasingly requires appropriate architectures and associated digital health solutions for the collection and management of large amounts of data. A reference architecture for the EMA-MCS platform with development directions and potential uses was described by Kraft et al. [41,76].

Sensors built in, or connected to, mobile devices are important in developing effective mobile diagnostics and therapy [77]. There are recent examples of how sensors can be built into smartphones for tinnitus treatment. Mehdi et al. [78] presented the Tinnitus Sense mobile app project, which aims to study the relationship between weather factors and the severity of tinnitus: weather data is collected automatically using smartphone sensors and visualized and managed by the app. Kraft et al. [76,79] presented a crowd sensing platform collecting a large amount of automatic data from sensors in smartphones in order to map areas with different noise levels, a facility that might help tinnitus patients avoid places with high noise levels.

Together with various miniaturized wearable diagnostic devices, sensors enable automatic collection of various biological, behavioral, and environmental data in real time; they can then make longitudinal measures of physiological functions that can be associated with the severity of tinnitus [62]. Nevertheless, attention needs to be paid to technological challenges, data protection, and anonymization, and the costs of carrying out this type of measurement [80].

Mobile apps are becoming increasingly popular in the control and management of smart devices for hearing and tinnitus therapy such as hearing aids (HAs) and cochlear implants (CIs). Searchfield et al. [62] describe the importance of rapidly developing technologically advanced smart hearing aids, cochlear implants, and smart headphones (hearables) in tinnitus therapy. HAs are used in tinnitus management to reduce the accompanying hearing handicap, reduce the attention paid to tinnitus, provide sound therapy, and raise the level of environmental sounds so that tinnitus can be effectively masked. Tinnitus sound therapy strategies developed for HAs are also being trialed with CIs. In the future, smart headphones with multiple functions (hearables) could be used as an alternative to HAs. Searchfield, referring to recent publications on the development of smart devices, noted that efforts to develop cognitively controlled HAs and ear-based EEGs could be extended to tinnitus treatment, with real-time adjustment based on AI [62]. The real promise of this technology is the potential to combine biometrics (e.g., EEG, heart rate, temperature, skin resistance, blood oxygen, and stress hormone levels) with auditory or other sensory stimulation.

Figure 1 summarizes the directions and technological background in the development of smartphone apps for tinnitus diagnosis and treatment. Appropriately combined, these possibilities may create the smart diagnostic and therapeutic platforms of the future. The platforms could offer personalized prediction models based on a real time assessment with AI support, as well as personalized care with constant and wide availability and just-in-time interventions.

Challenges and directions for future research

The systematic development of mobile technologies, including remote monitoring of a patient's health, will lead to innovative diagnostic and therapies with significant potential for health care systems.

Wide and constant access to diagnostic and therapeutic techniques, effective management of chronic diseases, and support for therapeutic decisions via mobile technologies are important developments in audiology. However, existing work in the field of self-measurement of hearing and tinnitus still need to be optimized, verified, and clinically proven before effective diagnostic methods can be introduced. In the area of diagnostics, then, a key factor is the scope and accuracy of self-measurement when used for the subjective and objective assessment of hearing. A similar comment relates to the assessment of the condition of the middle ear using modular portable devices together with a smartphone and a mobile app. Adapting these solutions to specific patient groups (e.g. older people) is a major consideration.

An important direction of research in audiology is the development of EMA methods. These will allow better control and management of chronic ailments such as tinnitus, in particular its progression, and how hearing levels improve or fluctuate as the result of various factors or use of therapeutic methods. The option of being able to have a reliable self-measurement, performed by the patient in real time and in natural conditions, might help create better predictive and diagnostic models. It will also enable more timely therapeutic responses during the course of tinnitus treatment. Just-in-time medical check-ups will not only increase the quality of therapy, but might also reduce treatment costs. Further research in this area will need clinically verified, accredited portable diagnostic tools for collecting automatic data (physiological, behavioral, environmental) in real time. The challenge will be to reduce the costs of these devices, adapting them for everyday use, taking into account patient motivation and eliminating technological and economic barriers (cost, access, and bandwidth). These solutions will require the creation of databases collecting large amounts of self-reported and automatic data of high quality. The challenge is to organize effective multidisciplinary cooperation in creating platforms to collect data, and then make it available to researchers, doctors, and patients. Legal regulations regarding the collection, management, and protection of sensitive data in these new systems will be an important issue.

The challenge for scientists and clinicians is to develop EMAI and JITAIs with the support of AI techniques. Designing automatic delivery of JITAIs, formulated by the app or by a doctor/therapist based on incoming data, will require an innovative approach in using existing scientific and therapeutic standards as well as new research into the dynamics of ongoing interventions. Nahum Shani et al. [67] emphasize the need for further efforts to develop dynamic theories of health behavior in the context of JITAIs. They claim that, despite the increasing use and appeal of JITAI, a major gap exists between the growing technological capabilities for delivering JITAIs and research on the development and evaluation of these interventions. Thus, there is a need for researchers and clinicians to be involved in the creation of JITAIs based on empirical evidence, theory, and accepted treatment guidelines. The authors point out that building an empirical basis on which to construct such dynamic models requires studies and methods that capitalize on the rich, fine-grained, temporal data that can now be collected using ubiquitous mobile and wireless technology. The basis for creating new dynamic behavioral models in medicine and their effective implementation are to be found in new study designs (e.g. MRT, micro-randomized trials) and data analytic methods (e.g. continuous updating of the JITAI decision rules depending on the effects of previous interventions). Additionally, Nahum Shani emphasize the need to train researchers in innovative approaches to creating study designs and analytic methods suitable for mobile health data.

In the context of EMAI and JITAIs, important factors in the introduction of innovative, more effective diagnostic and therapeutic methods is the chronic nature and variability of tinnitus and its susceptibility to various factors. Suitable methods will be needed to increase the effectiveness of therapeutic devices and hearing rehabilitation using hearing aids, cochlear implants, and other portable therapeutic devices. More effective methods will need to balance many factors, e.g. whether an individual suffers from hearing loss, tinnitus, or sound hypersensitivity.

In the area of tinnitus rehabilitation, previous findings suggest that mobile apps offer great potential for self-help therapeutic methods. They can be stand-alone methods or support methods offered by specialists. The introduction of clinically verified therapeutic methods based on mobile apps into the public health system will involve several stages. Therapeutic programs will need to be optimized in terms of intuitiveness and attractiveness. This is important for making independently run therapies effective and maintaining a high level of motivation. The next important step is to verify the efficacy of the apps in large randomized control clinical trials. Therapies based on mobile apps will also require linguistic and cultural adaptation in order to disseminate them around the world and perform clinical re-verification. The final challenge is to create educational programs for specialists – training modules – for individual mobile apps, setting out their therapeutic possibilities and areas of application.

Conclusions

1. Based on smartphone-based apps with ecological momentary assessments (EMAs), the possibility arises of using them and various wearable diagnostic devices to better understand the variability of tinnitus and its causes.
2. Combining mobile apps with mobile crowd sensing, central databases collecting anonymized user data, and AI support creates a valuable source for scientific research.
3. Clinically verified methods delivered by mobile apps could become part of a specialist-endorsed therapeutic process that supports easy, low-cost, and wide range therapy for dealing with tinnitus.
4. Multifunctional smart devices – such as hearing aids, cochlear implants, and hearables – and managed by mobile apps may become equally important in tinnitus therapy.
5. In the future, the development of mobile technologies and AI techniques will contribute to the creation of smart therapy platforms for tinnitus.

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