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Personal Music Players and Hearing Loss: The HUNT Cohort Study

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Abstract

It is unclear whether the current average use of personal music players (PMPs) including mobile phones has affected hearing in the general population. The association between the use of PMPs and hearing loss was assessed in a large population cross-sectional and follow-up study with the following distribution: cross-sectional (2018): $n = 26{,}606$, 56% women, mean age 54 years and 20-year follow-up (baseline 1998): $n = 12{,}115$, 57% women, mean age at baseline 43 years. Hearing threshold was determined as pure-tone average over the frequencies 3, 4, and 6 kHz. We used linear regression to assess relationships between hearing threshold and PMP use (yes), duration (1–2/2–6/>6 h per week), or sound volume (low/medium/high), with nonuse as reference. The PMP use increased from 8% in 1998 to 30% in 2018. Compared with nonusers, neither use nor duration was related to hearing threshold. As to sound volume, listening at low levels was associated with better thresholds (−2.5 dB [−4.1 to −0.8]), while listening at high levels was associated with worse thresholds (1.4 dB [0.1 to 2.8]). We adjusted for age, sex, baseline hearing threshold, education, noise exposure, ear infections, head injury, and daily smoking. The association with sound volume was nearly twice as strong when adjusting for hearing threshold at baseline. Accordingly, the possibility of reverse causality was reduced although not eliminated by the follow-up design. This large population study showed no association between normal PMP use and 20-year progression in hearing; however users listening to high levels increased their hearing threshold.

Keywords

headphone, music, noise, epidemiology, follow-up studies, adult

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Introduction

Leisure noise, and especially music listening, has received significant media attention with alarming headlines. More individuals listen to music through headphones or earbuds, and World Health Organization (WHO, 2015) estimates that 1.1 billion young people worldwide are at risk of hearing loss due to unsafe listening practices. The epidemiological evidence for an effect of music listening through personal music players (PMPs) on hearing has been limited and of low quality (European Commission—Scientific Committee on Emerging and Newly Identified Health Risks, 2008; Sliwinska-Kowalska & Zaborowski, 2017). Among more recent studies, all except one minor follow-up study (Marlenga et al., 2012) are cross-sectional (Båsjö et al., 2016; Berg & Serpanos, 2011; Henderson et al., 2011; Hong et al., 2016; Huh et al., 2016; Kumar et al., 2017; le Clercq et al., 2018; Lee et al., 2015; Le Prell et al., 2018; Marron et al., 2014; Rhee et al., 2019; Su & Chan, 2017; Swierniak et al., 2020; Twardella et al., 2016) in which interpretation of causality is difficult. Temporality, that the cause precedes the effect, is the only criterion considered by Rothman and Lash (2008) as a true causal criterion. It may be difficult, however, to ascertain the time sequence for cause and effect, which is crucial to exclude reverse causation, that the effect precedes the cause, for example, that hearing status affects

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the use of PMPs. There is therefore need for larger cohort studies and larger studies of the general population to study whether today's way of listening to music is a new threat to hearing.

This study was based on two large population-based cross-sectional hearing studies performed 20 years apart. We assessed the association between PMP use, as assessed by duration or volume level, and hearing threshold among adults using both cross-sectional and follow-up designs. The objective was to assess whether PMP use is a major risk factor for the average user in the general population. Another objective was to determine the possible role of reverse causation in the associations between PMP use and hearing threshold.

Methods

Participants

The Trøndelag Health Study (the HUNT Study) was a large general health-screening study for the entire adult population of Nord-Trøndelag County, Norway. The data were obtained through four population studies—the first one starting in 1984 and the last one ending in 2019. We used data from two hearing surveys as part of HUNT: HUNT2 Hearing (1996–1998) and HUNT4 Hearing (2017–2019). For simplicity, we use the years 1998 and 2018 to name the two surveys. The Regional Committees for Medical and Health Research Ethics approved the study (23178 HUNT hørsel). The study met all requirements in accordance with the General Data Protection Regulation and a Data Protection Impact Assessment was conducted. Only participants with written consent were included in the study.

HUNT2 Hearing included 17 of the 24 municipalities in the county. The participation rate was 63%, and altogether, 51,529 persons attended. HUNT4 Hearing took part in the six larger municipalities, representing about two thirds of the county. The participation rate was 43%, and altogether, 28,388 persons attended. The hearing studies are described in detail elsewhere (Engdahl et al., 2005, 2020).

This study included a cross-sectional sample of all persons attending HUNT4 Hearing ($n = 28{,}388$). Our study also included a follow-up sample of persons who attended both HUNT2 hearing and HUNT4 hearing ($n = 13{,}022$). After excluding persons with missing questionnaires or nonvalid audiometry, the final cross-sectional sample comprised 26,606 participants and the follow-up sample 12,115 participants.

Measurements

Both hearing studies included a questionnaire, otoscopy, and pure-tone audiometry. The participants filled out a detailed questionnaire in the waiting room before audiometry. The same audiometric procedure was followed for both studies. Pure-tone air-conduction hearing thresholds levels were determined in accordance with ISO 8253-1 (International Organization for Standardization, 2010), with fixed frequencies at the eight test frequencies 0.25, 0.5, 1, 2, 3, 4, 6, and 8 kHz, using an automatic procedure. Manual audiometry was offered to elderly or impaired subjects who were not able to follow the instructions for the automatic procedure. The audiometers were calibrated according to ISO 389-1 (International Organization for Standardization, 2017). Instead of using the original hearing thresholds relative to the reference zero of ISO 389, hearing thresholds were defined relative to the hearing thresholds levels of the population of otologically normal subjects aged 19 to 23 years in HUNT2 and HUNT4 (Engdahl et al., 2020). This was to compensate for possible systematic differences in calibration between audiometry in HUNT2 and HUNT4 when comparing absolute thresholds between the two surveys. When using relative thresholds, as in this study, the choice of reference does not matter, as the applied corrections are the same for all subjects. Detailed information about the measurements is described elsewhere for HUNT2 hearing (Engdahl et al., 2005) and HUNT4 hearing (Engdahl et al., 2020).

Outcome. We determined hearing threshold as pure-tone average over both ears and the frequencies 3, 4, and 6 kHz (PTA 3–6 kHz). As secondary outcomes, we estimated binaural thresholds at each specific frequency.

Exposure. PMP use in 1998 was estimated by the following question in HUNT2 Hearing: *Have you, for periods of at least 1 year, used a walkman or other type of "pocket disco" with earphones?* (never/rarely, 1–2 h per week, 2–6 h per week, and >6 h per week).

PMP use in 2018 was estimated by the following questions in HUNT4 hearing: *Have you, in periods of the last 20 year, used headphones or earbuds? (For example, when listening to music, watching TV/film or playing computer games).* (no, yes, and do not know). *If yes: How many hours per week have you used headphones or earbuds?* (never/rarely, 1–2 h per week, 2–6 h per week, and >6 h per week). *How high sound volume do you use most often?* (low, medium, and high).

The responses *no* or *do not know* on the filter question or *never-rarely* on the follow-up question was coded *never/rarely* to make the HUNT2 and HUNT4 questions comparable.

We constructed three categorical exposure variables: (a) use (never/rarely, yes), (b) duration (never/rarely, 1–2 h weekly, 3–6 h weekly, and >6 h weekly), and (c) sound volume level (never/rarely, low, medium, and high). Nonuser (never/rarely) was the reference category in all variables. We excluded subjects with missing values on PMP use from the analyses (these accounted for 3% in the HUNT4 and 8% in HUNT2).

For the purpose of illustrating the size of the exposure, we used the reported PMP duration per week and volume level to estimate a 40-h weekly A-weighted sound exposure, L_{Aeq8h}. This was by assuming that low-volume levels correspond to $L_{\text{Aeq}} = 70\,\text{dB}$, medium levels to $L_{\text{Aeq}} = 80\,\text{dB}$, and the high level to $L_{\text{Aeq}} = 90\,\text{dB}$, which has been suggested from rating loudness of PMP volume and loudness of leisure time noises found by others (Jokitulppo, 2003; Torre, 2008). Six hours of use per week at a level of 90 dB results in L_{Aeq8h} of about 82 dB.

Covariates. We obtained estimates of risk factors for hearing loss from similar questionnaires in HUNT2 and HUNT4 Hearing: occupational noise (regularly been exposed to loud noise at your present or previous work (no/less than 5 h/week, 5–15 h/week, >15 h/week); impulse noise (more often than most people, been exposed to impulse noise such as explosions, shooting, and so on (no, maybe, and yes); recurrent ear infections (no, maybe, and yes); hospitalization for head injuries (no, maybe, and yes); and smoking status (never daily smoking, previous daily smoking, and daily smoking). We treated missing values on any of these covariates as no exposure (these accounted for <5% for each variable). We obtained education attainment from national registers (primary school, secondary school, university <4 years, and university ≥ 4 years). All covariates were treated as continuous variables in the analyses.

Statistical Analyses

We used Stata version 16.0. Statistical tests were two-tailed and calculated at a 95% confidence interval. Linear regression was conducted to model the relationship between hearing threshold and PMP use, duration, or sound volume level. Never/rarely-use was reference category in all analyses. The associations were estimated in two different samples: (a) the follow-up sample (in order to investigate the association with or without adjustment for baseline hearing threshold) and (b) the full HUNT4 cross-sectional sample (in order to investigate the association in recent younger adults).

Follow-Up Sample (Participation in Both HUNT2 Hearing and HUNT4 Hearing). We assessed the relationship between hearing threshold at follow-up and PMP use, duration, or sound volume level in 2018. First with adjustment for age, sex, baseline hearing threshold, and all covariates (follow-up design), and second with adjustment for age, sex, and all covariates (cross-sectional design). Frequency-specific secondary analyses were separate regression models for the eight frequencies adjusting for age, sex, baseline hearing threshold, and all covariates.

We tested for interactions with age (Use × Age, Duration × Age, Volume × Age), and sex (Use × Sex, Duration × Sex, Volume × Sex). We also modeled the effect of different patterns of PMP use, being user and nonuser in 1998 and in 2018. Among users, we tested for interaction between sound volume and duration (Volume × Duration).

Full HUNT4 Hearing Cross-Sectional Sample. We assessed the relationship between hearing threshold and PMP use, duration, or sound volume level in the full HUNT4 cross-sectional sample. We tested for interactions with age (Use × Age, Duration × Age, Volume × Age) and then stratified in two age groups: <40 and ≥40 years of age. We adjusted for age, sex, and all covariates (no adjustment for baseline hearing threshold, only cross-sectional measurements).

The relation between age and hearing threshold is highly nonlinear. In all models, age was therefore modeled as a restricted cubic spline with five knots with default knot locations, as this created a better model fit than simpler models with age as a linear variable for all models tested (Likelihood-ratio test, $p < .001$). A cubic spline is essentially a smooth curve constructed from piecewise cubic polynomials restricted to be smooth at the junction or knot of each polynomial. A restricted cubic spline has the additional property that the curve is linear before the first knot and after the last knot. Transforming the continuous predictor using restricted cubic splines provides a simple way to create, test, and model nonlinear relationships in regression models (Harrell, 2001).

Results

The follow-up sample (participants in both HUNT2 and HUNT4) included 12,115 participants with mean age 43 years (19–79) at baseline, and there were 57% women (Table 1). The average follow-up time was 21 years (19–23) with an average decline in hearing threshold over the period of 17 dB. The use of PMPs among the participants was nearly doubled from 973 (8%) in 1998 to 1,836 (15%) in 2018. There were relatively few consistent users of PMP in both 1998 and 2018: Several users stopped using PMPs (592 of 973) and several nonusers started to use PMPs (1,408 of 10,596).

The full HUNT4 cross-sectional sample included 26,606 participants with mean age 54 years (19–100; Table 1). The use of PMPs increased from 8% in 1998 to 30% in 2018 and among 20 to 39 years old from 17% to 66% (data not shown). In 2018, 7% used PMPs more than 6 h per week, and 7% reported that they most often used PMPs with high sound volume; 475 subjects (2%)

Table 1. Sample Description.

	Follow-up sample ($n = 12{,}115$)		Cross-sectional sample ($n = 26{,}606$)
	1998	2018	2018
Age, years	42.8 (11.1)	64.0 (11.0)	53.6 (16.9)
PTA hearing threshold 3–6 kHz, dB	12.6 (14.0)	30.2 (20.6)	21.7 (20.5)
Females	6,863 (57%)		14,981 (56%)
PMP use			
Never/rarely	10,596 (87%)	9,992 (82%)	17,945 (67%)
Yes	973 (8%)	1,836 (16%)	8,094 (31%)
Missing	546 (5%)	287 (2%)	567 (2%)
PMP duration			
Never/rarely	10,596 (87%)	9,992 (82%)	17,945 (67%)
1–2 h per week	629 (5%)	943 (8%)	3,367 (13%)
3–6 h per week	199 (2%)	593 (5%)	2,951 (11%)
>6 h per week	145 (1%)	300 (2%)	1,776 (7%)
Missing	546 (5%)	287 (2%)	567 (2%)
PMP sound volume			
Never/rarely		9,992 (82%)	17,945 (67%)
Low		170 (1%)	494 (2%)
Medium		1,401 (12%)	5,586 (21%)
High		251 (2%)	1,955 (7%)
Missing		301 (2%)	626 (2%)
Education			
Primary school	2,044 (17%)	1,705 (14%)	3,597 (14%)
Secondary school	6,922 (57%)	6,725 (56%)	13,034 (49%)
University <4 years	2,690 (22%)	3,069 (25%)	7,987 (30%)
University ≥ 4 years	459 (4%)	616 (5%)	1,988 (7%)
Occupational noise exposure			
No never	7,394 (61%)	9,103 (75%)	19,797 (74%)
<5 h per week	2,131 (18%)	746 (6%)	1,879 (7%)
5–15 h per week	1,199 (10%)	1,166 (10%)	2,624 (10%)
>15 h per week	1,391 (11%)	1,100 (9%)	2,306 (9%)
Impulse noise exposure			
No	10,423 (86%)	9,894 (82%)	21,748 (82%)
Maybe/do not know	842 (7%)	604 (5%)	1,309 (5%)
Yes	850 (7%)	1,617 (13%)	3,549 (13%)
Recurrent ear infections			
No	8,972 (74%)	10,332 (85%)	22,089 (83%)
Maybe/do not know	654 (5%)	251 (2%)	661 (2%)
Yes	2,489 (21%)	1,532 (13%)	3,856 (14%)
Hospitalization for head injuries			
No	11,327 (93%)	11 (93%)	24,578 (92%)
Maybe/do not know	87 (1%)	88 (1%)	276 (1%)
Yes	701 (6%)	769 (6%)	1,752 (7%)
Daily smoking			
No	5,733 (47%)	5,586 (46%)	21,333 (43%)
Previous	3,339 (28%)	5,526 (46%)	13,610 (27%)
Yes	3,043 (25%)	1,003 (8%)	13,621 (27%)

Note. Data are *n* (%) or mean (standard deviation). PTA = pure-tone average; PMP = portable media player.

used PMPs more than 6 h per week and with high sound volume. Among 20 to 39 years old, 18% used PMPs more than 6 h per week, 23% used PMPs with high sound volume, and 6% reported use both more than 6 h per week and with high sound volume (data not shown).

Follow-Up Sample

Linear regression models of hearing threshold at follow-up (PTA 3–6 kHz, averaged over both ears) and PMP use, duration, or sound volume in 2018 were executed 2 times. First adjusted for baseline hearing threshold (follow-up design) and second without adjustment for baseline hearing threshold (cross-sectional design). Because estimates with and without adjustment for covariates were similar (<3% change) only fully adjusted models are presented (Table 2). Neither PMP use nor the duration of use per week was related to hearing threshold, $F(3, 11812) = 0.98$, $p = .40$; Table 2 rightmost column. This was true also for frequency specific, secondary outcome, analyses (Figure 1). The preferred sound volume was, however, related to hearing threshold, $F(3, 11798) = 5.551$, $p = .0008$. Compared with nonusers, listening at low-volume levels was associated with better thresholds (−2.5 dB) while listening at high levels was associated with worse thresholds (1.4 dB) shown by the regression coefficients in Table 2, which are adjusted differences in thresholds between each volume level and the reference group never/rarely use. Frequency-specific, secondary outcome, analyses revealed that this association was mainly found for frequencies at and above 2 kHz with similar effects at 8 kHz as for the 3, 4, and 6 kHz included in the main outcome (Figure 2). There were no significant interactions with age or sex: In other words, the association between PMP use and hearing threshold, duration and hearing threshold, or volume and hearing threshold did not depend on either age or sex. Among PMP users, there was no statistically significant interaction between sound volume and the duration of use per week, so the association between PMP volume and hearing threshold was similar for all levels of duration and participants with combined high-volume and high-duration exposure showing no worse hearing thresholds than participants with high-volume and low-duration exposure.

In the model not adjusting for hearing threshold at baseline (Table 2 leftmost column), the estimated association with preferred sound volume level was nearly twice as strong.

There was an association between hearing threshold and the different patterns of use, $F(3, 11293) = 2.68$, $p = .045$. Users in 1998 that stopped using PMPs in 2018 had better thresholds compared with those who did not use PMPs neither in 1998 nor in 2018 adjusting for covariates and hearing threshold at baseline (−1.08 dB [−1.98 to −0.16], $p = .022$). Nonusers in 1998 that used PMPs in 2018 and users in both 1998 and 2018 had nonsignificantly better thresholds than those who did not use PMPs neither in 1998 nor in 2018 (−0.58 [−1.20 to 0.33], $p = .064$) respectively (−0.69 [−1.83 to 0.46], $p = .241$).

Full HUNT4 cross-sectional sample

We also assessed the effect of PMP use, duration, or volume on hearing threshold (PTA 3–6 kHz) in the complete HUNT4 cross-sectional sample. Analysis of the cross-sectional sample revealed a significant interaction between sound volume and age, indicating that the effect of PMP volume on hearing threshold was larger among older adults than among younger adults. Results were therefore stratified in two age groups, <40 and ≥40 years (Table 3). There was a relation between sound volume level and hearing threshold in both age groups, <40 years: $F(3, 5995) = 4.24$, $p = .005$, ≥40 years: $F(3, 19869) = 13.49$, $p < .00001$. Elevated thresholds as compared with nonusers were only observed among users of high-volume levels in the older age group. There was a weak association between duration of use

Table 2. Association Between PMP Use in 2018 and PTA Hearing Threshold at 3, 4 and 6 kHz in 2018.

			Cross-sectional design[a]			Follow-up design[b]		
		n	Coefficient	[95% CI]	*p*	Coefficient	[95% CI]	*p*
Use	Never/rarely	9,992	Ref			Ref		
	Yes	1,836	−0.87	[−1.62, −0.11]	.025	−0.47	[−1.02, 0.08]	.095
Duration	Never/rarely	9,992	Ref			Ref		
	1–2 h per week	943	−0.80	[−1.80, 0.20]	.115	−0.38	[−1.11, 0.35]	.303
	3–6 h per week	593	−0.98	[−2.22, 0.25]	.119	−0.60	[−1.50, 0.30]	.192
	>6 h per week	300	−0.83	[−2.53, 0.87]	.340	−0.49	[−1.74, 0.75]	.437
Sound volume	Never/rarely	9,992	Ref			Ref		
	Low	170	−4.72	[−6.95, −2.49]	.00003	−2.46	[−4.08, −0.83]	.003
	Medium	1,401	−0.99	[−1.84, −0.15]	.021	−0.57	[−1.19, 0.05]	.070
	High	251	2.22	[0.36, 4.08]	.020	1.42	[0.06, 2.78]	.040

Note. Multiple linear regression. Follow-up sample. $n = 12{,}115$. Coefficient = regression coefficients in dB, with 95% uncertainty intervals in parentheses. Regression coefficients are adjusted differences in thresholds between each level of duration/volume and the reference group never/rarely use; PTA = pure-tone average. PMP = portable media player. Missing data on PMP use and duration, $n = 333$(3%) and sound volume, $n = 347$ (3%). Adjusting for age, sex, education, occupational noise exposure, impulse noise exposure, recurrent ear infections, head injury, and daily smoking in all models. CI = confidence interval.

[a]Not adjusting for baseline PTA hearing threshold at 3, 4, and 6 kHz.

[b]Adjusting for baseline PTA hearing threshold at 3, 4, and 6 kHz.

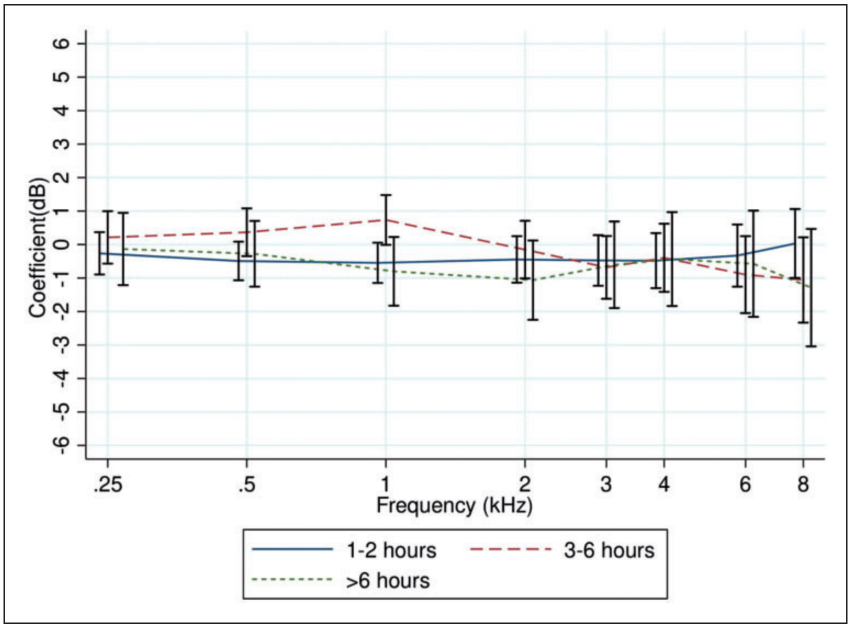

Figure 1. Linear Regression Models of the Relationship Between Binaural Hearing Threshold and PMP Duration in Hours Use Per Week, With Separate Models for Each Frequency at .25 to 8 kHz. Regression coefficients in dB for PMP duration with 95% confidence intervals are presented. Regression coefficients are adjusted differences in thresholds between each level of duration and the reference group never/rarely use. Adjusted for age, sex, baseline hearing thresholds, education, occupational noise exposure, impulse noise exposure, recurrent ear infections, head injury, and daily smoking.

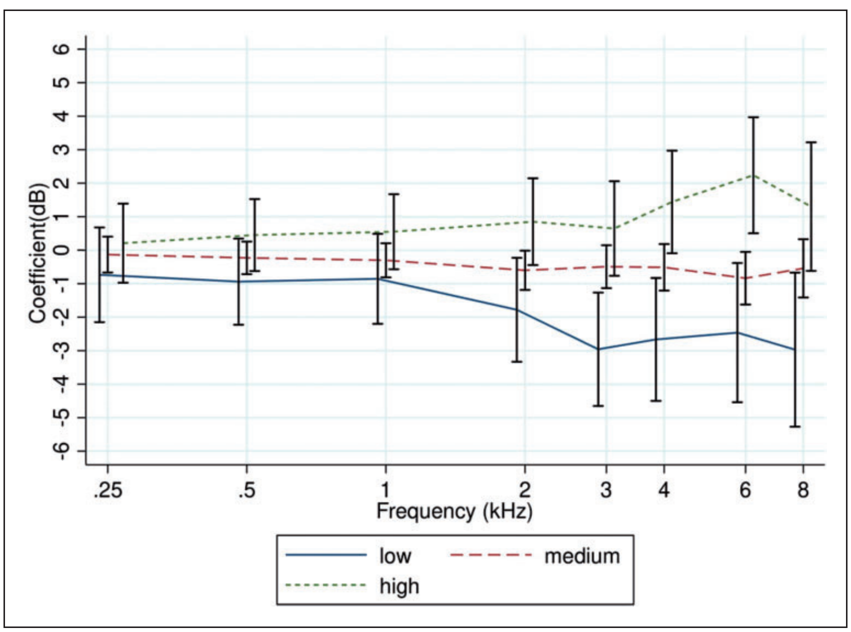

Figure 2. Linear Regression Models of the Relationship Between Binaural Hearing Threshold and PMP Sound Volume, With Separate Models for Each Frequency at .25 to 8 kHz. Regression coefficients in dB for PMP volume with 95% confidence interval are presented. Regression coefficients are adjusted differences in thresholds between each volume level and the reference group never/rarely use. Adjusted for age, sex, baseline hearing thresholds, education, occupational noise exposure, impulse noise exposure, recurrent ear infections, head injury, and daily smoking.

Table 3. Association Between PMP Use in 2018 and PTA Hearing Threshold at 3, 4, and 6 kHz in 2018.

		Aged 20–39 years ($n = 6{,}135$)				Aged 40–99 years ($n = 20{,}471$)			
		n	Coefficient	[95% CI]	*p*	n	Coefficient	[95% CI]	*p*
Use	Never/rarely	1,966	Ref			11,357	Ref		
	Yes	4,097	−0.74	[−1.17, −0.31]	0.001	9,114	−0.62	[−1.08, −0.17]	0.007
Duration	Never/rarely	1,966	Ref			15,979	Ref		
	1–2 h per week	1,368	−0.50	[−1.02, 0.03]	0.063	1,999	−0.73	[−1.40, −0.06]	0.033
	3–6 h per week	1,610	−0.47	[−0.99, 0.04]	0.071	1,341	−0.75	[−1.55, 0.06]	0.068
	>6 h per week	1,119	−0.50	[−1.08, 0.09]	0.098	657	−1.05	[−2.17, 0.07]	0.067
Sound volume	Never/rarely	1,966	Ref			15,979	Ref		
	Low	170	−1.52	[−2.71, −0.34]	0.012	324	−3.93	[−5.48, −2.38]	0.000
	Medium	2,579	−0.62	[−1.08, −0.17]	0.007	3,007	−0.91	[−1.48, −0.34]	0.002
	High	1,320	−0.11	[−0.65, 0.44]	0.704	635	1.34	[0.21, 2.48]	0.021

Note. Multiple linear regression. Cross-sectional sample. $n = 26{,}606$. Coefficient = regression coefficients in dB, with 95% uncertainty intervals in parentheses. Regression coefficients are adjusted differences in thresholds between each level of duration/volume and the reference group never/rarely use. PTA = pure-tone average. PMP = portable media player. Missing data on PMP use $n = 72$ (1%) and 495 (2%). Adjusting for age, sex, education, occupational noise exposure, impulse noise exposure, recurrent ear infections, head injury, and daily smoking. CI = confidence interval.

per week and hearing threshold in the above 40 year group only, with better thresholds among users than non-users, <40 years: $F(3, 6023) = 1.70$, $p = .16$, ≥40 years: $F(3, 19869) = 3.10$, $p = .025$.

Discussion

There was a large increase in the use of PMPs from 1998 to 2018. We found no association between PMP use (yes/no) or the duration (hours per week) and the 20-year progression in hearing threshold at 3 to 6 kHz. However, we found a positive relation between listening to higher sound volume levels and hearing threshold. The association was half as strong when adjusting for hearing threshold at baseline. Analyses of the cross-sectional sample indicated that the association with sound level increased by age.

We have only found one previous follow-up study of PMP use (Marlenga et al., 2012). Marlenga et al. followed up 243 children (aged 14.5 years, 12–16, at baseline) in 16 years and estimated decline in hearing threshold of 15 dB or more at any of the high frequencies (3, 4, or 6 kHz) in either ear. The highest exposure group ($n = 53$) had used PMP in 2,080 h (936–36,400) for a period of 13 years. The lowest exposure group was non-users ($n = 137$). Odds ratio (OR) comparing highest to lowest group (excluding middle group) was 0.65 [0.35 to 1.24] and OR comparing sound volume from very high to low was 1.19 [0.51 to 2.78]. Although none of their results were statistically significant, the direction of the effects agrees with our findings. The studies differ in terms of power and age distribution with ages below 30 at follow-up in their study compared with our 40+.

Our finding of no associations with PMP use in general is in agreement with previous cross-sectional analyses from HUNT2 hearing (Tambs et al., 2003) and studies from the large general population cohorts of U. S. youths, National Health and Nutrition Examination Survey (NHANES). Henderson et al. reported the prevalence of noise-induced hearing loss from NHANES in 1996/1998 and 2005/2006, which included 4,311 subjects aged 12 to 19 years. Among these subjects, 1,122 reported to have been exposed to loud noise or listening to music through headphones the last 24 h (Henderson et al., 2011). The study showed no effect on the prevalence of audiometric notches at 3, 4, or 6 kHz ($OR = 0.94$ [0.65 to 1.35]) after adjusting for age, sex, race, and income. Su and Chan (2017) reported similar results from the waves of NHANES in 2005/2006, 2007/2008, and 2009/2010, which included 4,064 subjects aged 12 to 19 years. The study showed no effects on hearing loss of 15 dB or more at low frequencies, high frequencies, or on audiometric notches.

Results reported from the large Korean general population cohort Korea National Health and Nutrition Examination Survey (KNHANES) were inconsistent. Lee et al. reported hearing thresholds from KNHANES (2009–2011) of 4,810 adults (>19 years). The study showed increased thresholds at low frequencies in subjects with a history of earphone use in noisy environments (1.024 dB [0.176 to 1.871], $p = .018$) but not at high frequencies (Lee et al., 2015). Hong et al. reported prevalence of hearing loss in KNHANES of 1,658 adolescents (age 13–18 years). Earphone use in noisy environment was associated with bilateral hearing loss at high frequencies ($\chi^2 = 4.52$, $p = .027$) but not with bilateral hearing loss at speech frequencies or unilateral hearing losses (Hong et al., 2016). Huh et al. analyzed hearing loss in 1,036 earphone users in KNHANES (2010–2013) out of 7,596 subjects aged 10 to 87 years. They found a relation between earphone use time and prevalence of hearing loss ($OR = 1.19$ per hour use/day [1.01 to 1.41]; Huh et al., 2016).

Several reviews have summarized the risk of developing permanent hearing loss due to the use of PMP. The report of the Scientific Committee on Emerging and Newly Identified Hazards and Risk in 2008 showed no direct evidence for an effect of repeated, regular daily exposures to music listened to through PMPs on the development of permanent hearing loss (European Commission—Scientific Committee on Emerging and Newly Identified Health Risks, 2008). One more recent review added three additional small cross-sectional studies of PMP use and permanent hearing loss published in the period 2008–2015 (Sliwinska-Kowalska & Zaborowski, 2017). They concluded that there was low-quality GRADE (Grading of Recommendations, Assessment, Development and Evaluations) evidence that prolonged listening to loud music through PMPs increases the risk of hearing loss and results in worsening standard frequency audiometric thresholds. The authors pointed to the limitation that all studies were cross-sectional. One systematic review that included a search until 2015 (le Clercq et al., 2016) showed no significant differences in the prevalence of hearing loss between children, adolescents, and young adults who were exposed to loud music in general and those who were not. Pooled cross-sectional data from seven studies of PMP use found small but significant differences between users and nonusers at 4, 6, and 8 kHz of 1, 2, and 3 dB, respectively. Finally, a recent review included a search until 2019 (You et al., 2020). The authors pooled results from seven cross-sectional studies including five recent studies that were not included in the previous reviews. The study showed small, pooled, associations of PMP use and hearing threshold at 6 and 8 kHz only (effect size, Hedges' *g*, 0.52 and 0.49, respectively).

We found listeners to high-volume levels to have 1.4 dB elevated thresholds. If we assume that high-volume level corresponds to $L_{Aeq} = 90$ dB, 6 h of PMP use per week results in a 40-h weekly noise exposure of about 82 dB. This corresponds well with the noise-induced permanent threshold shift that is expected from 20 years of 40-h weekly noise exposure at 82 dB of about 1.8 dB according to ISO 1999 (International Organization for Standardization, 2013). It is a crude estimate as no clear definition of high or medium sound volume was given to the subjects, and participants' perception of high or loud sound volume can be vastly different among individuals. Also, the equal-energy principle that states that equal energy, the function of sound level and duration, will cause equal damage, was not fully supported by our results as we found no association between duration and hearing threshold regardless of the volume level the participants reported using most often.

Our study is unique in terms of being the first large population-based follow-up study that assesses the impact of average PMP use, as assessed by duration and volume, on hearing thresholds. Our findings add to existing knowledge in two important ways. First, we found no effects of normal PMP use on long-time hearing decline in the general population. This is of high importance in terms of public health concern. The burden of hearing loss is expected to increase due to that world's population is aging rapidly (WHO, 2019). While factors like prevention of occupational noise may reduce this elevation (Engdahl et al., 2020), there have been concerns that unsafe listening habits to PMP may influence hearing loss also at a population level (WHO, 2015). Second, PMP users listening to a high sound volume increased their progression of hearing loss. Sounds from earbuds or earphones are most likely as harmful as occupational noise at the same sound level. Therefore, documenting excess risk among the most exposed warrant further measures to keep listening to PMPs safe.

The major strengths of our study are the large sample size, standardized audiometric measurements, that our cohorts are representative of a large general adult population, and the longitudinal design. The follow-up design lowers the likelihood of reverse causality most likely present in previous cross-sectional studies. We found that the association between sound volume and hearing threshold was nearly twice as large in cross-sectional analysis compared with estimates from the follow-up analysis adjusting for hearing at baseline. This may suggest that associations estimated in cross-sectional studies to a large extent can be interpreted as reversely causal. Indication of reverse causality is found in a study showing that adolescents with congenital hearing loss listened to louder sound volumes most likely to compensate for their hearing loss (Widen et al., 2018). The risk of reverse causality may be more plausible in the elder population in which the occurrence of hearing loss is higher than in adolescents and young adults. This may have contributed to the larger associations that we found in cross-sectional analyses among the older subjects.

Limitations

First, the exposure is assessed retrospectively using self-report sensitive to recall bias—which means the accuracy of recall regarding prior exposures may differ for study subjects depending on their disease status. Typically, recall bias is assumed to exaggerate estimates of effect size as cases are assumed to have better recall of prior exposures than controls, in particularly for exposure that has been given much public attention.

Second, we have no measure of exposure duration in years and we cannot separate short- versus long-time users of PMPs. However, the effect of noise exposure is known to be largest for the first 5 years of exposure (International Organization for Standardization, 2013). Our subjects were all above 40 years at follow-up and more than a quarter of the users also used PMPs at baseline 20 years earlier. We therefore believe the exposure duration to be long enough.

Third, despite the benefit of the present follow-up design that allowed control for hearing loss at baseline and thus minimizing the risk of reverse causality, reverse causality cannot be ruled out. Subjects developing hearing loss during follow-up may, as mentioned, turn up their volume of PMPs. The association with sound volume was frequency dependent, with effects mainly at higher frequencies. This indicates that the volume setting causes hearing loss, rather than the other way around. Noise exposure is generally observed to increase hearing loss mainly at the higher frequencies, especially at 4 to 6 kHz (Rösler, 1994) while a hearing loss is likely to affect people's volume setting equally regardless of the frequency of the hearing loss.

Fourth, the analyses of effects of different patterns of PMP use in 1998 and 2018 was restricted to the duration of use as preferred volume setting was not assessed in 1998. Also, subjects developing hearing loss may stop using PMPs altogether, equally to the *sick-quitter* effect found in alcohol research. However, this is unlikely as we found less progression in hearing loss among users that stopped using PMPs between the two waves.

Finally, this study was restricted to pure-tone hearing thresholds at conventional frequencies. It might be that the use of PMP may influence other aspects of hearing not necessarily related to pure-tone hearing thresholds such as tinnitus, hyperacusis, and the ability to detect sounds in background noise. It may also be that the effects of PMP use may be detected by measures that are more sensitive than pure-tone hearing thresholds at conventional frequencies such as otoacoustic emissions and hearing thresholds in the extended high-frequency range.

Conclusion

While we found no negative association between the duration of PMP use per se and 20-year progression in hearing at the general population level, users listening to high-volume levels increased their hearing thresholds. Together with available evidence, this suggests that most regular PMP use does not affect people's hearing substantially. However, certain groups may be at risk, such as those with prolonged listening to a high sound volume. Due to the observational design, one must be cautious to evaluate the finding as strictly causal. Longitudinal studies with detailed exposure classification and more frequent follow-up are warranted.

Data Accessibility Statement

The data from the Trøndelag Health Study are stored in HUNT databank. HUNT Research Centre has permission from the Norwegian Data Inspectorate to store and handle these data. The key identification in the data base is the personal identification number given to all Norwegians at birth or immigration, while de-identified data are sent to researchers upon approval of a research protocol by the Regional Ethical Committee and HUNT Research Centre. To protect participants' privacy, HUNT Research Centre aims to limit storage of data outside HUNT databank and cannot deposit data in open repositories. HUNT databank has precise information on all data exported to different projects and is able to reproduce these on request. There are no restrictions regarding data export given approval of applications to HUNT Research Centre. For more information, see http://www.ntnu.edu/hunt/data.

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