

Environmental noise exposure and autoimmune diseases: Evidence from a national cohort study

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ABSTRACT

Exposure to environmental noise is an inevitable factor and may pose a risk to health conditions, even potentially affecting the immune system. However, the relationship between noise exposure and autoimmune diseases has not been well explored. This study aimed to investigate whether noise exposure is associated with an increased risk of autoimmune diseases in South Korea. We analyzed data from the National Health Insurance Service (NHIS) cohort from 2013 to 2019. Environmental noise data were provided by the National Noise Information System (NNIS) and spatially interpolated using empirical Bayes kriging (EBK) to estimate noise levels at the district level. Both daytime and nighttime noise were assessed, with mean noise exposure values calculated for each administrative district. The HR were estimated using the Cox proportional hazards model, along with standardized incidence ratios (SIRs) for autoimmune diseases. A trend analysis was also performed to examine the association between cumulative noise exposure and autoimmune disease incidence. High noise exposure was significantly associated with an increased risk of autoimmune diseases (HR 1.03; 95 % CI: 1.01–1.05), including higher SIRs for Rheumatoid Arthritis, Systemic Lupus Erythematosus, Hashimoto's disease, and Graves' disease. A significant trend was observed, with greater noise exposure correlating with higher autoimmune disease incidence, particularly for total and daytime noise. This study provides evidence of a significant association between high environmental noise exposure and increased risk of autoimmune diseases, indicating noise as a modifiable risk factor.

1. Introduction

Autoimmune diseases are complex chronic conditions characterized by a breakdown in immune tolerance, leading to dysregulation and abnormal activation of both innate and adaptive immunity. This dysfunction causes the immune system to produce autoantibodies that mistakenly target the body's own tissues, resulting in persistent inflammation across multiple organs (Conrad et al., 2022). The prevalence of autoimmune diseases is estimated to be 4 %–5 %, with projections suggesting they will affect 15–20 million individuals in the coming decades (Hernández-Negrín et al., 2021). The total direct medical spending on autoimmune disorders is substantial and continues to increase rapidly (Miller, 2023).

Although numerous studies have linked the onset of autoimmune

diseases to non-modifiable factors such as gender and genetic susceptibility, the complex etiology and pathogenesis of autoimmune diseases remain not fully understood (Conrad et al., 2023). Meanwhile, recent studies indicate the role of modifiable factors such as smoking, dietary habits, and environmental pollution as potential risk factors for the development of autoimmune diseases (Bieber et al., 2023; Lee et al., 2023a).

Noise, an unwanted or unpleasant sound that is pervasive and generally unnoticed in daily life, is known to pose significant health risks due to its unavoidable exposure. To date, multiple studies have proven the association between noise exposure and hearing impairment, attributing sensorineural hearing deficit to damage caused to cochlear hair cells (Hesse and Kastellis, 2019). Additionally, our previous study summarized the extra-auditory effects of noise exposure, including a

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range of chronic diseases such as cancer, respiratory and endocrine disorders, digestive disorders, as well as effects on the reproductive system, the nervous system, neurodegenerative diseases, and even the immune response (Lee et al., 2023b). The mechanism by which noise exposure triggers immune responses involves its impact on cortisol and epinephrine levels, which are known to exert significant influence on the immune system. This impact induces the continuous release of inflammatory cytokines, hsCRP, and the breakdown of triacylglycerol, potentially increasing the risk of developing autoimmune diseases (Selander et al., 2009; Tait et al., 2019). These findings suggest that noise extends beyond being a mere environmental exposure factor, implying its multifaceted influence with comprehensive adverse effects on human health.

However, previous studies have primarily focused on high-level or acute noise exposure in relation to autoimmune diseases, sometimes reporting an indirect association through chronic noise exposure and degenerative noise-induced disorders rather than direct effects (Berker et al., 2012; Dzhambov and Dimitrova, 2017; Eryilmaz et al., 2007). Moreover, previous studies have focused on a limited subset of the over 100 recognized autoimmune diseases, resulting in insufficient information on the broader risk of various autoimmune diseases associated with noise exposure.

In this study, we investigated the association between daytime and nighttime noise exposure and a series of autoimmune diseases, categorized based on the InterLymph classification, using data from the National Health Insurance Service–National Sample Cohort (NHIS–NSC) and noise data from the National Noise Information System (NNIS) in South Korea.

2. Materials and methods

2.1. Study participants and sample collection

We used data from the NHIS–NSC (2002–2019) in South Korea. The NHIS provides mandatory public health insurance that covers medical care services consisting of national health insurance, medical aid, and long-term care insurance to all individuals residing in Korea (Lee et al., 2017). In 2002, the NHIS–NSC used a systematic sampling method to obtain data for 1025,340 regionally representative, randomly selected individuals out of all 46,605,433 Korean residents. It was an anonymized dataset that included insurance type, socioeconomic characteristics (age, sex, income level, and region), medical and hospital use history, and health examination results from January 2002 to December 2019. Medical service data were based on the standardized protocol of the International Classification of Diseases, 10th revision (ICD-10), and included records of all covered medical expenditures and prescriptions (Chun ChangBae et al., 2009).

2.2. Autoimmune diseases categorization

Autoimmune diseases were classified using the InterLymph classification, which includes criteria such as the presence of chronic inflammatory features, overactivation or abnormal regulation of immune function, and the extent of association with non-Hodgkin lymphoma (NHL) (Wang et al., 2015). Based on the extent of organ involvement, autoimmune diseases were grouped into systemic connective tissue diseases and organ-specific diseases. ICD-10 coding schemes were used to identify diagnoses from health records (Conrad et al., 2022).

2.3. Environmental noise and estimations of noise exposure

Environmental noise data from 2002 to 2019, provided by the NNIS, were used to analyze the relationship between noise exposure and autoimmune diseases. The NNIS offers two types of environmental noise data based on different measurement methods: automatic and manual. In this study, the noise levels by district were identified using manually

obtained NNIS data. The manual noise measurements were conducted using sound level meters that comply with the Class 1 specifications outlined in IEC 61672–1 standards. To minimize potential biases, noise measurements were conducted under standardized environmental conditions. Measurements were taken during periods with stable meteorological conditions, avoiding extreme weather such as strong winds or heavy rainfall. The height of the microphone was consistently maintained between 1.2 and 1.5 m above ground level, as per ISO 1996–1 guidelines. Noise readings were recorded at least 3.5 m away from reflective surfaces or obstacles that could distort sound levels. Environmental noise data were categorized into two groups based on the time of measurement: daytime and nighttime noise. Daytime noise levels were measured four times between 6:00 AM and 10:00 PM, while nighttime noise was measured twice between 10:00 PM and 6:00 AM, ensuring a minimum interval of two hours between measurements. During preprocessing, any noise data with inaccuracies were filtered out from the dataset provided by the National Noise Information System. The preprocessed dataset included 1188 measurement points across 94 areas at minimum and 1681 points across 120 areas at maximum, depending on the year.

Noise levels were estimated for areas where measurements were not available. In general, environmental noise levels can be considered a geographical phenomenon because the spatial distribution of noise levels is mainly influenced by the spatial characteristics of noise sources (Murphy and King, 2022). Therefore, estimating noise levels across the target area through spatial interpolation is a viable approach. In this study, the collected data were interpolated with empirical Bayes kriging (EBK) to determine the environmental noise level of the entire target area. EBK spatially interpolates data by iteratively improving the model's performance and estimates. Unlike traditional kriging methods, EBK employs localized model simulations, making it particularly suitable for estimating values in deficient areas with limited data (Krivoruchko, 2012). Based on the collected noise values, we used EBK to create an environmental noise raster map covering the entire study area and calculate the average noise values for each administrative unit. Fig. 1 shows the annual average daytime and nighttime noise levels for the entire region from 2002 to 2019.

For nighttime noise, a cutoff value of 55 dB was applied based on the World Health Organization (WHO) nighttime noise guidelines (2009), which recommend a target value of 55 dB for interim night noise levels (Hurtley, 2009). For daytime noise, there was limited academic consensus on the cutoff value. We used 65 dB as the standard for daytime noise in Korea, which is the level that needs to be managed, and divided it into two groups.

2.4. Covariates

Sex, age, household income, and type of insurance were used to describe the socioeconomic status of the participants. Based on health examination results of the NHIS–NSC, body mass index (BMI), smoking status, and drinking status were selected as covariates related to health status.

2.5. Statistical analysis

Baseline characteristics and noise exposure levels were described using the Chi-square test, based on autoimmune diseases that newly occurred during the follow-up period in the initial cohort. A Cox proportional hazard model was used to estimate the hazard ratios (HR) and 95 % confidence intervals (CI) for autoimmune diseases related to daytime and nighttime noise, in which noise was considered a time-variable covariate. We estimated the age-standardized incidence ratios (SIRs) and 95 % CIs of autoimmune diseases according to high exposure to daytime and nighttime noise using all participants in the NHIS–NSC as the reference group. Trend analysis between cumulative noise exposure levels and autoimmune disease incidence was conducted after adjusting for sex, age, household income, type of insurance, BMI, smoking, and

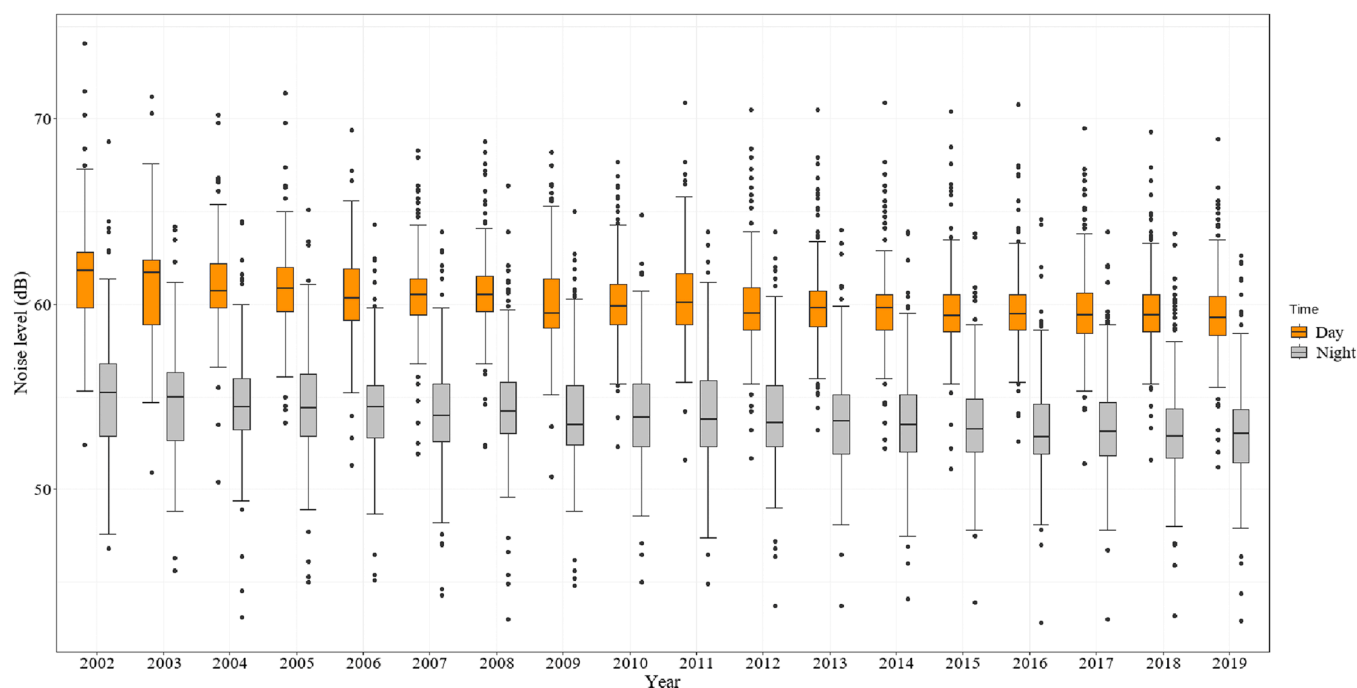


Fig. 1. Annual mean of daytime and nighttime noise levels during the follow-up periods (2002–2019). The figure demonstrates the spatial distribution of average noise levels across administrative units, showing variations in daytime and nighttime noise over time.

drinking. All analyses were performed using SAS, version 9.4 (SAS Institute, Cary, NC, USA).

3. Results

This study included a total of 564,503 participants, of whom 61,277 (10.9 %) had an autoimmune disease. Table 1 summarizes the baseline characteristics of the study population stratified by autoimmune disease status. The highest proportions of participants with autoimmune diseases were observed among women (59.2 %) and those aged 41–60 years (42.7 %). Other notable proportions included those with high household incomes (26.7 %), normal BMIs (62.3 %), and never smokers (68.9 %). Additionally, participants who reported no drinking or social drinking habits (86.7 %) and those exposed to low daytime noise (89.9 %) and high nighttime noise (57.0 %) were also predominant.

Table 2 presents the hazard ratios (HRs) and 95 % confidence intervals (CIs) for patients with autoimmune diseases. The proportion of women (HR 1.39, 95 % CI: 1.36–1.42), those aged 41–60 years (HR 2.41, 95 % CI: 2.34–2.50), those with high household incomes (HR 1.03, 95 % CI: 1.01–1.06), those enrolled in the Medical Aid insurance program (HR 1.26, 95 % CI: 1.20–1.33), those classified as overweight by BMI (HR 1.02, 95 % CI: 1.01–1.04), past smokers (HR 1.07, 95 % CI: 1.04–1.10), and severe drinkers (HR 1.05, 95 % CI: 1.03–1.08) was significantly higher than in the reference group. Moreover, high daytime noise (HR 1.05, 95 % CI: 1.02–1.08) and nighttime noise (HR 1.03, 95 % CI: 1.01–1.05) were associated with an increased risk of autoimmune diseases compared with the reference group.

Fig. 2 shows the age-SIRs and 95 % CIs of autoimmune diseases, including organ-specific and connective tissue diseases, in relation to high noise exposure during daytime and nighttime. With high noise exposure during the nighttime, the SIR for RA was 1.03 (95 % CI: 1.01–1.04), and the SIR for SLE was 1.12 (95 % CI: 1.03–1.21) among connective tissue diseases. Among organ-specific diseases, the SIR for Graves' disease was 1.07 (95 % CI: 1.01–1.13), which was statistically significant. With high noise exposure during the daytime, the SIRs for the organ-specific conditions Hashimoto's disease and Graves' disease were 1.46 (95 % CI: 1.36–1.56) and 2.25 (95 % CI: 2.05–2.46),

respectively.

Incidences and trends of autoimmune diseases according to the type and level of noise exposure are presented in Fig. 3. The result revealed a statistically significant positive correlation between the incidence of autoimmune diseases and increasing levels of total noise exposure ($\beta=0.1967$, $R^2=0.9528$, $p=0.0432$) as well as daytime noise exposure ($\beta=0.2056$, $R^2=0.9515$, $p=0.0216$). However, no statistically significant association was found between nighttime noise exposure and the incidence of autoimmune diseases ($\beta=0.1785$, $R^2=0.9735$, $p=0.0561$).

4. Discussion

This study establishes a significant association between environmental noise exposure, both daytime and nighttime, and the risk of autoimmune diseases. We found that women, individuals aged 41–60, those with higher household incomes, overweight individuals by BMI, and former smokers, all with known autoimmune disease risk factors, showed increased hazard ratios for autoimmune diseases. Additionally, significant SIRs were observed for RA, SLE, Graves' disease, and Hashimoto's disease in relation to noise exposure levels.

Noise pollution, along with air pollution, is one of the most significant environmental threats to public health (EK, 2014). Consistent with our findings, some studies reported an elevated risk of specific autoimmune diseases associated with various sociodemographic factors, including occupational and environmental noise (De Roos et al., 2014; Emamifar et al., 2016; Wu et al., 2024). Additionally, a research proved a correlation between noise exposure and heightened severity of collagen-induced arthritis in vivo (Rogers et al., 1983).

Although the mechanism linking noise to autoimmune diseases remains unclear, some studies have suggested that noise affects various bodily systems, including the central nervous, endocrine, digestive, and respiratory systems, thereby influencing immune function. Noise exposure is associated with alterations in thyroid hormone levels, evidenced by increased plasma triiodothyronine (T3) and decreased thyroid-stimulating hormone (TSH) levels, as well as changes in thyroid pathology, including increased full follicles and decreased empty follicles,

Table 1
Characteristics of study participants of the National Health Insurance Service–National Sample Cohort with and without autoimmune diseases.

	Autoimmune diseases, n (%)		p-value
	No	Yes	
Total participants	503,226 (89.1)	61,277 (10.9)	
Sex			<0.0001
Men	255,795 (91.1)	24,972 (8.9)	
Women	247,431 (87.2)	36,305 (12.8)	
Age (years at enrollment)			<0.0001
≤20	69,903 (94.1)	4376 (5.9)	
21–40	222,091 (91.6)	20,265 (8.4)	
41–60	163,991 (86.2)	26,157 (13.8)	
> 61	47,241 (81.8)	10,479 (18.2)	
Household income			<0.0001
Low	93,661 (89.1)	11,499 (10.9)	
Low–moderate	82,649 (89.8)	9417 (10.2)	
Moderate	88,532 (89.7)	10,202 (10.3)	
High–moderate	114,385 (89.2)	13,825 (10.8)	
High	123,999 (88.4)	16,334 (11.6)	
Type of insurance			<0.0001
NHI employee subscriber	83,743 (88.5)	12,144 (11.5)	
NHI employee dependent	101,027 (89.5)	11,814 (10.5)	
NHI district subscriber	152,062 (91.1)	14,946 (8.9)	
NHI district dependent	146,343 (87.5)	20,843 (12.5)	
Medical aid	10,051 (86.8)	1530 (13.2)	
Body mass index			<0.0001
Underweight	25,147 (89.9)	2821 (10.1)	
Normal	317,130 (89.2)	38,204 (10.8)	
Overweight	160,949 (88.8)	20,252 (11.2)	
Smoking status			<0.0001
Never smoker	309,598 (88.0)	42,215 (12.0)	
Past smoker	64,042 (89.5)	7484 (10.5)	
Current smoker	129,586 (91.8)	11,578 (8.2)	
Drinking status			<0.0001
None or social	423,979 (88.9)	53,121 (11.1)	
Severe	79,247 (90.7)	8156 (9.3)	
Daytime noise			0.0038
Low (≤65 dB)	454,127 (89.2)	55,073 (10.8)	
High (>65 dB)	49,099 (88.8)	6204 (11.2)	
Nighttime noise			0.0288
Low (≤55 dB)	218,506 (89.3)	26,323 (10.7)	
High (>55 dB)	28,4720 (89.1)	34,954 (10.9)	

observed in rats after long-term exposure (Ababzadeh et al., 2021). Moreover, experimental studies on male workers revealed that for every 10 dB increase in noise level, there were significant decreases in T4 levels and increases in TSH levels (Khosravipour et al., 2021). This evidence suggests a potential link between noise exposure and thyroid dysfunction, which could contribute to the development of Graves’ disease and Hashimoto’s disease. Thereby, noise could act as an environmental stressor, triggering cortisol and catecholamine production, altering immune cell proliferation, cytokine secretion, and antibody production (Kim et al., 2017; Padgett and Glaser, 2003; Zheng and Ariizumi, 2007).

Our study indicated novel findings regarding the relationship between noise exposure and autoimmune diseases using NHIS–NSC data renowned for its representation of the general population and quality assurance measures. Moreover, our findings provide unique perspectives on autoimmune diseases based on Asian ethnic and geographic baselines compared with studies conducted in Western studies.

However, it is important to acknowledge the limitations of this study when interpreting the results. First, this study was based on medical claims data; however, because detailed clinical information was not available, it was not possible to know the diagnostic criteria used to diagnose autoimmune diseases. Therefore, the possibility of inaccurate diagnoses of autoimmune diseases cannot be ruled out. Second, individuals with high socioeconomic status may have greater access to diagnosis and treatment (Petersen and Kwan, 2011), and our findings revealed that patients with autoimmune diseases had higher household incomes. Consequently, the analysis may have been affected by

Table 2
Hazard ratios (HR) and 95 % confidence intervals (CI) for autoimmune diseases.

	Autoimmune diseases, HR (95 % CI)
Sex	
Men	Reference
Women	1.39 (1.36–1.42)
Age (years at enrollment)	
≤ 20	Reference
21–40	1.48 (1.43–1.53)
41–60	2.41 (2.34–2.50)
> 61	2.30 (3.09–3.32)
Household income	
Low	Reference
Low–moderate	0.98 (0.95–1.01)
Moderate	0.99 (0.96–1.01)
High–moderate	1.01 (0.98–1.03)
High	1.03 (1.01–1.06)
Type of insurance	
NHI employee subscriber	1.07 (1.05–1.10)
NHI employee dependent	1.02 (0.99–1.05)
NHI district subscriber	Reference
NHI district dependent	1.08 (1.05–1.10)
Medical aid	1.26 (1.20–1.33)
Body mass index	
Underweight	0.99 (0.95–1.03)
Normal	Reference
Overweight	1.02 (1.01–1.04)
Smoking status	
Never smoker	Reference
Past smoker	1.07 (1.04–1.10)
Current smoker	0.95 (0.93–0.98)
Drinking status	
None or social	Reference
Severe	1.05 (1.03–1.08)
Daytime noise	
Low (≤65 dB)	Reference
High (>65 dB)	1.05 (1.02–1.08)
Nighttime noise	
Low (≤55 dB)	Reference
High (>55 dB)	1.03 (1.01–1.05)

underreporting of NHIS–NSC data and undiagnosed cases of autoimmune diseases (Calixto and Anaya, 2014). Third, environmental factors other than noise exposure, such as particulate matter, were not considered in the analysis. Recent studies have demonstrated that air pollutants, including particulate matter, are linked to the onset and progression of autoimmune diseases. Therefore, future studies should investigate both noise and air pollution as key exposure variables (Zhao et al., 2019). *Future studies could integrate particulate matter and other air pollutants (e.g., NO₂, SO₂, or ozone) as additional exposure variables to evaluate their independent and combined effects with noise pollution on autoimmune disease risk. Employing multi-exposure models, such as mixed-effects or Bayesian hierarchical models, can disentangle the contributions of various environmental stressors. Additionally, geospatial analyses combining noise and air pollution data could help assess their co-exposure effects on health outcomes, particularly in urban areas where these factors often overlap.* Finally, the reliance on residential addresses and outdoor measurements to estimate noise exposure using the kriging method, without accounting for indoor noise levels, may have introduced bias. Despite previous studies indicating a strong association between indoor and outdoor noise levels (Naim et al., 2018; Ryu and Jeon, 2011), there are still limitations due to the use of Geographic Information System (GIS) spatial analysis to estimate noise levels in areas without sufficient noise information. The designated noise measurement points were chosen based on factors such as population and area. Therefore, our kriging method may not have provided accurate noise information in regions with lower measurement priority. *To address this issue, future research could apply the following methods to refine environmental exposure estimates. Specifically, incorporating mobility data to understand daily activity patterns, utilizing advanced noise mapping techniques such as smartphone-based real-time noise assessments, and estimating lifetime noise*

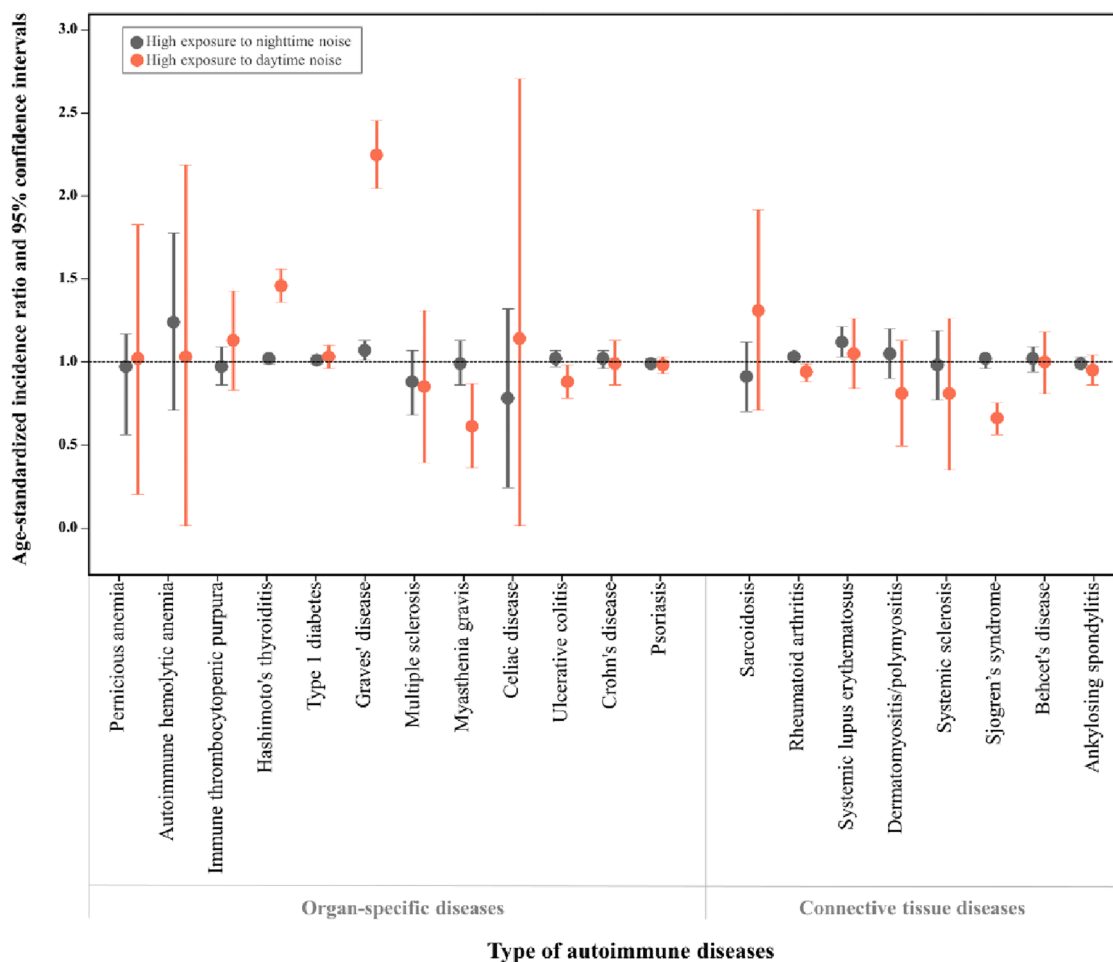


Fig. 2. Age-standardized incidence ratios (SIRs) and 95 % confidence intervals for autoimmune diseases by noise exposure levels. The result depicts the relationship between high noise exposure (daytime and nighttime) and the incidence of autoimmune diseases. Autoimmune diseases are stratified into organ-specific diseases and connective tissue diseases. Red markers indicate high daytime noise exposure, and gray markers represent high nighttime noise exposure. The horizontal dashed line at SIR = 1.0 indicates the null value, with deviations reflecting increased or decreased risk.

exposure through structured interviews such as the Noise Exposure Structured Interview (NESI) could improve accuracy. Additionally, integrating indoor and occupational noise measurements using personal noise dosimeters could provide a more comprehensive exposure profile. These strategies are expected to not only improve noise exposure assessments, but also reduce potential bias, making future studies more robust.

The United Nations Environment Programme (UNEP) pointed out that noise pollution leads to various public health problems and identified it as a critical issue requiring concentrated efforts by governments and local authorities (John, 2023). While noise is an inevitable environmental factor, it remains a modifiable risk. Therefore, to protect public health, it is crucial to implement more stringent noise regulation standards and to elevate public awareness regarding the potential health impacts of noise exposure.

In conclusion, this study found a significant association between environmental noise exposure and an increased risk of autoimmune diseases, with elevated noise levels linked to higher HR and statistically significant trends in age-specific incidence rates using data analysis of NHIS-NSC and NNIS data. These findings suggest that noise exposure is a significant modifiable risk factor for autoimmune diseases. Further research is required to strengthen the evidence supporting these results.

Ethics approval

The Institutional Review Board of the Gil Medical Center, Gachon University, approved this study (IRB number: GCIRB2021-380).

Authors' contributions

Y.L. and X.M. designed the study and wrote the manuscript. S.L. and X.M. contributed to data collection. S.L. and W.L. performed the statistical analysis and interpreted the results. All authors read and approved the final manuscript.

Consent for publication

All participants provided written informed consent.

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CRediT authorship contribution statement

Xiaoxue Ma: Writing – original draft. **Seunghyun Lee:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Wanhyung Lee:** Writing – original draft, Visualization, Formal analysis. **Yongho Lee:** Writing – original draft, Methodology, Investigation, Conceptualization.

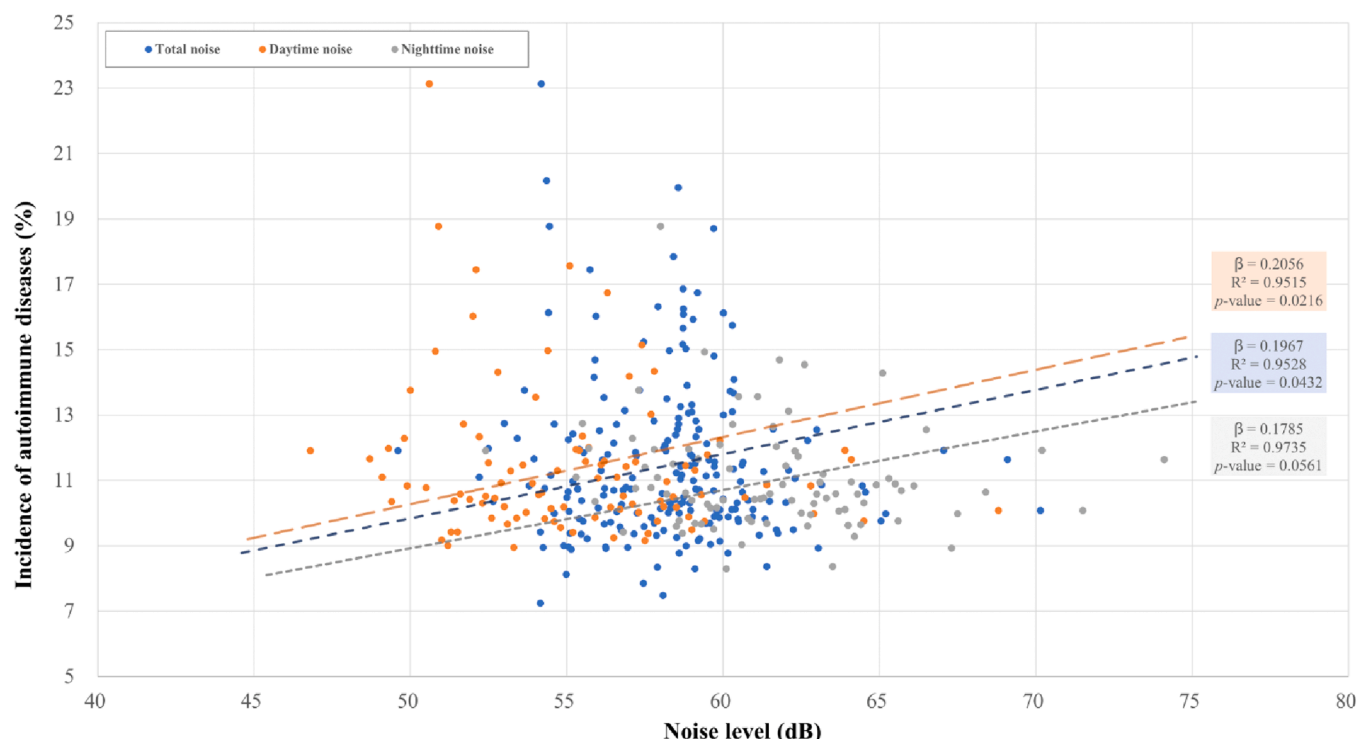


Fig. 3. Incidence and trends of autoimmune diseases stratified by noise exposure type and cumulative levels. The figure illustrates the relationship between environmental noise levels (dB) and the incidence rates (%) of autoimmune diseases. Noise exposure is stratified into total noise (blue), daytime noise (orange), and nighttime noise (gray), with each regression line representing the exposure-specific trend.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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