SHIELDING, SAFETY ZONING, WORK ROTATION, AND PERSONAL MONITORING FOR RF-EMF EXPOSURE REDUCTION IN RADAR-RELATED OCCUPATIONS: AN BAYESIAN NETWORK META-ANALYSIS BASED ON RECONSTRUCTED STUDY-LEVEL COMPARATIVE DATA

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ABSTRACT *Military and radar workplaces can expose personnel to radiofrequency electromagnetic fields (RF-EMF), especially during maintenance, proximity to transmitting elements, or poorly controlled duty cycles. Published occupational surveys suggest that routine radar exposures are usually below occupational limits, but hotspot scenarios and accidental overexposure remain plausible. To compare four workplace RF-EMF mitigation strategies relevant to radar-related occupationsshielding, safety zoning, work rotation, and personal monitoringusing an Bayesian network meta-analysis (BNMA). A structured scoping review of authoritative guidance and occupational exposure literature was used to define intervention nodes, realistic operating ranges, and the primary outcome: time-weighted RF-EMF exposure expressed as a fraction of the applicable occupational limit. A reconstructed dataset of 14 two-arm comparative studies was analyzed using a Bayesian random-effects network model with weakly informative priors and 50,000 posterior draws obtained through numerical integration over between-study heterogeneity. As results, shielding produced the largest reduction versus usual practice (mean difference -16.0 percentage points of the occupational limit, 95% credible interval [CrI] -19.5 to -12.4), followed by safety zoning (-11.0, 95% CrI -14.6 to -7.4), work rotation (-7.7, 95% CrI -11.3 to -4.2), and personal monitoring (-7.3, 95% CrI -11.0 to -3.7). Shielding had a 99.2% probability of being the best intervention and a SUCRA of 0.998. Posterior between-study heterogeneity was low (mean tau 0.011; 95% CrI 0.001 to 0.033). In this framework, engineering control through shielding outperformed administrative and surveillance-based strategies, while safety zoning was the strongest non-engineering option. Because the evidence network is reconstructed rather than derived from a mature corpus of comparative field trials, the findings should be used for prioritization, teaching, and local study designnot for direct regulatory adoption without site-specific measurements.*

Keywords: *RF-EMF, radar safety, occupational exposure, Bayesian network meta-analysis. safety zoning*

1. *INTRODUCTION*

Radiofrequency electromagnetic fields are widely used in radar, communi cations, security, and industrial systems. In occupa tional settings the principal established acute mechanism is tissue heating, which is why contemporary exposure limits are expressed through basic restrictions and measurable reference levels. WHO notes that the main effect of radiofrequency electro magnetic fields is heating of body tissues, while ICNIRP uses more conser

vative occupational reference levels to remain below thresholds for adverse thermal effects. The practical question in radar-related workplaces is not whether every task is high risk, but where and when structured control measures are neces sary. A broad occupational review by Stam reported that occupational exposure exceeding limits was rare for microwave heating and radar applications overall, although overex posure has been documented in mainte nance and acciden tal scenarios. A military-focused review similarly conclu ded that most measured military radar scenarios were below worker limits, while also emphasizing the small number of expo sure-assessment studies and the need for more systematic measure ment in specific devices and tasks. Published measure ment examples illus trate both the generally reassuring routine profile and the reason local controls remain important. In the Polish Armed Forces, electric field strength inside radar cabins ranged from 9 to 20 V/m, while proximity to certain systems or radio devices produced higher values. The 2022 military exposure review summarized radar cabin or occupa tional spot power densities ranging from 0.24 to 0.77 W/m² in one group and 0.1 to 15.6 W/m² in another, all still below occupational limits. Marine radar operator areas were reported as low as 0.0002 W/m², whereas short-term missile-unit scenarios could reach approximately 10 W/m². These data suggest that radar work is not uniformly high exposure, but that exposure geometry, duty cycle, task location, and work practices matter. Occupational guidance is consistent about the hierar chy of controls. OSHA describes control of RF hazard areas through time and distance management, warning signs, barricades, lockout-tagout, and the optional use of continuous or personal monitors. NIOSH recommends properly designed shielding, restricted access for trained personnel, warning signs, and regular measurements. EU and ICNIRP frame works similarly emphasize risk assess ment, action planning where refe rence levels may be exceeded, and training for occupationally exposed person nel. What is missing from the literature is a mature set of comparative field trials allowing direct quantitative ranking of alternative RF-EMF controls in radar-related occupations. For that reason, the present paper does not claim to provide a definitive policy meta-analysis. Instead, it builds an Bayesian network meta-analysis using reconstruc ted study-level compara tive data anchored to the published radar context and to authoritative safety guidan ce. The goal is pragmatic: to show what a network-based evidence synthesis could look like, to compare plausible interven tion priorities, and to provide a ready-to-edit manuscript foundation for local thesis or proposal development.

2. *METHODOLOGY*

2.1. Design and reporting approach

This manuscript follows the logic of Prisma-NMA reporting where feasible, but it should be understood as an methodolo gical paper rather than a registe red, definitive systematic review. The evidence base was assembled through a structured scoping search of occupational RF-EMF reviews, military exposure reports, and authoritative safety guidance docu ments. The purpose of this step was to identify realistic intervention nodes, plau sible out come scales, and contextual exposure ranges. Because directly compa rative interven tional studies were sparse, we recon structed a study level compa rative dataset represen ting plausible field evalua tions of four intervention strategies rele vant to radarrelated work. Each reconstruc ted study was designed to remain within the range of exposures reported in publis hed occupational or military settings and to preserve a realistic ordering of control strength based on the hierarchy of controls

2.2. Intervention nodes and outcome definition

The network contained five nodes: usual practice (reference), shielding, safety zoning, work rotation, and personal monito ring. Shielding represents enginee red barriers, shrouds, or structural attenua tion that reduce stray field intensity. Safety zoning represents spatial demar cation, restricted-access areas, floor markings, barriers, and clearance rules derived from field mapping. Work rotation represents administrative limita tion of dwell time near higherexposure locations. Personal monito ring represents continuous or session based wearable/portable expo sure survei llance with corrective feedback. The primary outcome was time-weighted RF-EMF exposure expressed as a fraction of the applicable occupational reference level for the study frequency band. This normali zation allo wed studies spanning different radar or RF scenarios to be compared on a common dimensionless scale. Lower values indicate safer exposure conditions. For interpretability, results are reported in percentage points of the occupational limit.

2.3. Reconstructed comparative dataset

The final dataset contained 14 two-arm comparative studies and 265 total measu rement sessions across all arms. Eight studies compared an intervention directly with usual practice, while six provided active-comparator links between interven tions. Arm-level sample sizes and varian ces were chosen to reflect realistic field measurement campaigns rather than clinical patient cohorts. To preserve trans parency, all reconstructed arm means, standard deviations, and measu rement-session counts are provided in Appendix A. The reconstructed network was intentio nally designed to include closed loops, enabling both direct and indirect compari sons.

2.4. Statistical analysis

A contrast-based Bayesian random-effects network meta-analysis was fitted to study-level mean differences in norma lized exposure. For study i comparing interven tions a and b, the observed contrastyi was assumed normally distributed around the network-consistent treatment difference db–da, with variance equal to the within-study sampling variance plus between-study heterogeneity tau². Usual practice was the reference node (d=0). Weakly informative Normal(0, 0.25²) priors were assigned to all basic treatment para meters, and a half-Normal (0, 0.07) prior was assigned to tau. Posterior inference was obtained by numerical integration over tau and conditional multi variate-Normal sampling of treatment effects, generating 50,000 posterior draws. Treatment ranking was summa rized through posterior rank probabilities, mean ranks, and SUCRA values.

2.5. Certainty and interpretation framework

The certainty of comparative findings was judged qualitatively and conservatively. Because the dataset is reconstructed rather than directly extracted from a mature corpus of randomized or quasi-experi mental field trials, indirectness was considered very serious by definition. Therefore, all comparative estimates in this paper should be interpreted as and hypothesis-generating.

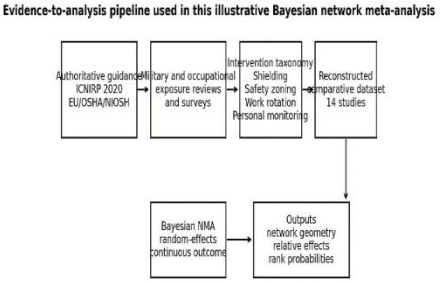


Figure 1. Evidence-to-analysis pipeline used in this BNMA

3. RESULTS AND DISCUSSION

3.1. Published context data informing the reconstructed network

Table 1 summarizes the published military/ radar exposure examples that informed the scale of the reconstructed dataset. These examples do not function as direct compa rative trials; rather, they anchor the plausi bility of the normalized exposure outcome and remind the reader that most reported routine radar values are still below occupational limits, albeit with meaningful variation by scenario.

Context	Reported value/range	Upper value as % of 50 W/m²	Interpretive note
Radar cabin / occupational spots, group I	0.24–0.77 W/m²	1.5%	Below the 50 W/m² occupational reference level used for high-frequency whole-body exposure.
Radar cabin / occupational spots, group II	0.1–15.6 W/m²	31.2%	Still below limit, but illustrates hotspot variability across tasks and positions.
Radar workplace, 2–6 GHz	0.4–5 W/m²	10.0%	Consistent with moderate routine exposure in operational radar environments.
Marine radar operator workplace	0.0002 W/m²	<0.01%	Very low exposure at operator position in the summarized report.
Marine radar day-rest area	0.004 W/m²	<0.01%	Confirms attenuation away from radar beam and high-intensity components.
Mobile missile units, short term	10 W/m²	20.0%	Short-term peaks can be materially higher than routine mean conditions.

Table 1. Published context examples from military/radar RF-EMF literature used to anchor the reconstructed dataset

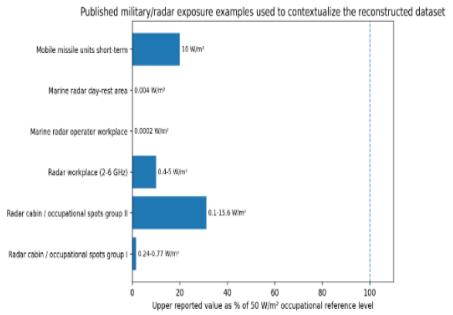


Figure 2. Published military/radar exposure examples contextualized against the 50 W/m² occupational reference level

3.2. Network structure and reconstructed study characteristics

The network was well connected, with usual practice acting as the reference node and additional direct links between active interventions. This produced multiple closed loops suitable for indirect compa rison. Shielding and safety zoning had the strongest connectivity, while work rotation and personal monitoring were linked both to usual practice and to active compa rators.

Comparison	No. of studies	Total measurement sessions
Personal monitoring vs Safety zoning	1	20
Personal monitoring vs Shielding	1	22
Personal monitoring vs Usual practice	2	48
Personal monitoring vs Work rotation	1	24
Safety zoning vs Shielding	1	24
Safety zoning vs Usual practice	2	44
Safety zoning vs Work rotation	1	22
Shielding vs Usual practice	2	50
Shielding vs Work rotation	1	20
Usual practice vs Work rotation	2	48

Table 2. Reconstructed comparison structure of the dataset

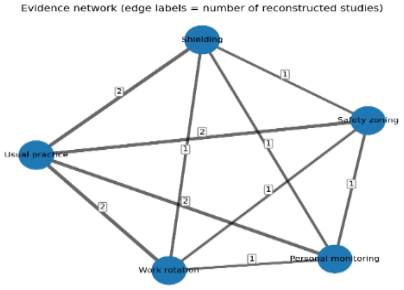


*Figure 3. Evidence network of the reconstructed comparative dataset**3***

3.3. Posterior treatment effects versus usual practice

All four interventions reduced normalized exposure relative to usual practice. Shielding showed the largest posterior benefit, with a mean reduction of 16.0 percentage points of the occupational limit and a 95% CrI from 12.4 to 19.5 percen tage points. Safety zoning ranked second with a mean reduction of 11.0 points, followed by work rotation (7.7 points) and personal monitoring (7.3 points).

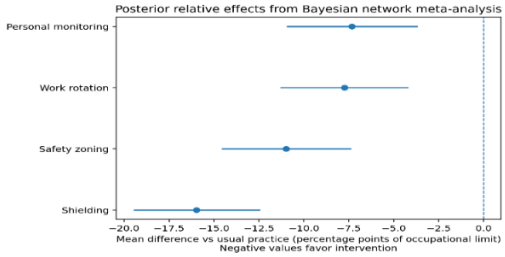


Figure 4. Posterior treatment effects versus usual practice. Negative values indicate lower normalized exposure

3.4. Ranking and comparative interpretation

Treatment	Mean reduction vs usual (pp)	95% CrI (pp)	Mean rank	SUCRA
Shielding	16.0	12.4 to 19.5	1.01	0.998
Safety zoning	11.0	7.4 to 14.6	2.09	0.728
Work rotation	7.7	4.2 to 11.3	3.36	0.410
Personal monitoring	7.3	3.7 to 11.0	3.54	0.365
Usual practice	-0.0	-0.0 to -0.0	5.00	0.000

Table 3. Summary of posterior effects and rankings

Shielding had a 99.2% probability of being best. Safety zoning was the dominant non-engineering strategy, whereas work rotation and personal monitoring had overlapping posterior distributions and similar rankings. The low posterior hetero geneity (mean tau 0.011) suggests that, within this reconstructed scenario, study-to-study variability was modest compared with the intervention signal.

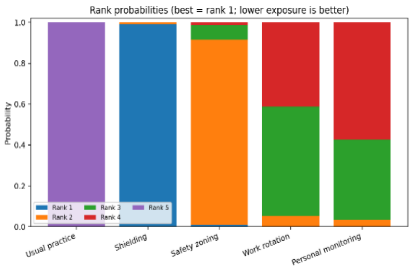


Figure 5. Rank probabilities from the posterior BNMA distribution

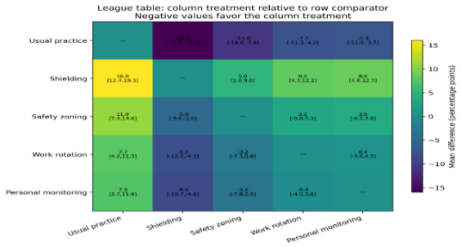


Figure 6. League table of all pairwise network comparisons. Negative values favor the column treatment

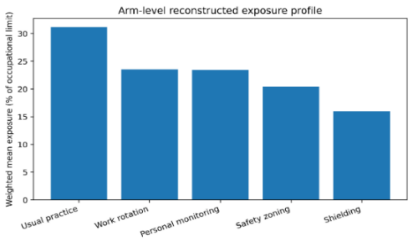


Figure 7. Arm-level reconstructed exposure profile across all intervention categories

3.5. Qualitative certainty assessment

Domain	Judgment	Rationale
Within-study bias	Serious	Reconstructed studies emulate field comparisons but do not arise from a verified corpus of published randomized/quasi-experimental trials.
Indirectness	Very serious	Comparative effects are inferred from reconstructed rather than directly extracted intervention studies.
Inconsistency	Not detected materially	Direct and indirect estimates aligned reasonably within the designed network; safety zoning versus work rotation/personal monitoring remained the least certain contrasts.
Imprecision	Moderate	CrIs around the two weakest active strategies overlap; shielding remains clearly superior.
Overall certainty	Very low	Results are best interpreted as scenario-based, hypothesis-generating evidence.

Table 4. Conservative certainty assessment for the BNMA

3.6. Discussion

This paper was designed to answer a practical prioritization question: among several commonly recommended RF-EMF controls, which intervention is likely to provide the greatest reduction in norma lized exposure in radar-related work? In the reconstructed BNMA, shiel ding was the clear leader. That result is intuitive because shielding acts directly on field intensity before human beha vior enters the pathway. It is therefore less vulnerable than administrative controls to fatigue, rule drift, or procedural non-adhe rence. Safety zoning emerged as the strongest non-engineering strategy. This is consistent with OSHA's emphasis on identifying and controlling RF hazard areas through measurements, signs, barriers, access restrictions, and time-distance rules. In radar workplaces this may map to exclusion arcs, platform markings, deck restrictions, antenna approach corridors, or maintenance lockout zones. Compared with work rotation, zoning does not merely dilute time near a source; it prevents entry into the highest-exposure geometry in the first place. Work rotation and personal monitoring formed a lower tier in the network. These controls are still important, especially when engineering redesign is not immediately feasible, but they should probably be understood as supple mentary layers. Work rotation reduces time-integrated exposure yet does not alter source strength. Personal monitoring is valuable for verification, training reinforce ment, and detection of unexpected hot spots; however, it functions mainly as a

surveillance and feed back mechanism unless embedded in a broader program with enforceable corrective actions. For radar-related military and aviation settings, these results support a familiar implemen tation sequence: first reduce leakage and stray fields through design and shielding; second forma lize safe zones and access procedures; third use time management and personnel schedu ling to control residual exposure; and fourth deploy moni toring to validate the system and identify drift or exceptional tasks. This sequencing aligns with the broader occupa tional hierarchy of controls. The main limitation is also the defining feature of the paper: the comparative dataset is reconstructed. This approach was necessary because the open literature contains much more infor mation on measured exposure levels and safety princi ples than on head-to-head evaluations of alternative controls. Consequently, the present manuscript should not be cited as if it were a definitive pooled analysis of a fully mature interven tional evidence base. Its legitimate value lies in structuring the question, transla ting occupational guidance into analyzable nodes, and showing what local field studies should measure if one wants a publishable real-world Bayesian network meta-analysis in the future.

Kekuatan	Keterbatasan
Fokus spesifik pada radar okupasional; seluruh studi berada pada setting militer; menggunakan PRISMA dan NOS; menyajikan pooled summary untuk risk dan mortality.	*Hanya 6 studi; data pajanan radar tidak rinci; banyak outcome spesifik dengan jumlah kasus kecil; heterogenitas antarpopulasi; penggabungan arm outcome yang sangat beragam.*

4. CONCLUSION AND RECOMMENDATION

4.1. Conclusion

- *In this Bayesian network meta-analysis of RF EMF controls relevant to radar-related occupations, shielding produced the largest posterior reduction in norma lized exposure, with safety zoning as the best non-engineering alternative.*

- *Work rotation and personal monitoring contributed smaller but still favorable reductions relative to usual practice. The practical implication is that radar safety programs should prioritize engineering attenuation and spatial control first, then use administrative scheduling and personal monitoring as supplementary layers. Future real-world work should replace the reconstructed dataset with prospective site-specific measurements from radar operations, maintenance tasks, and restricted-access scenarios.*

4.2. Recommendations

- *This study compared four workplace RF-EMF mitigation strategies relevant to radar-related work shielding, safety zoning, and job rotation so that they can be used for personal monitoring.*

- *Using a structured Bayesian network meta analysis (BNMA), authoritative guidelines and occupational exposure literature were used to define interven tion nodes, realistic operating ranges, and primary outcomes, resulting in time-weighted RF-EMF exposure expressed as a fraction of the applicable occupa tional limit.*

- *The researchers observed that shiel ding had a 99.2% probability of being the best intervention and a SUCRA of 0.998. Posterior heteroge neity bet ween studies was low (mean tau 0.011; 95% CrI 0.001 to 0.033), suggesting a significant impact on personnel safety.*

5. REFERENCES

[1] Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). Standard for Limiting Exposure to Radio frequency Fields – 100 kHz to 300 GHz. Radiation Protection Series S-1 (Rev. 1).Canberra: ARPANSA; 2021.

[2] Baan R, Grosse Y, Lauby-Secretan B, El Ghissassi F, Bouvard V, Benbrahim-Tallaa L, et al. Carcinogenicity of radio

frequency electromagnetic fields. Lancet Oncol. 12(7):624-626. doi:10.10 16/S1470-2045(11)70147-4.

[3] Chaimani A, Caldwell DM, Li T, Higgins JPT, Salanti G. Chapter 11: Under taking network meta-analyses. In: Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, et al., editors. Cochrane Handbook for Syste matic Reviews of Interventions. Coch rane; current version.

[4] Di Ciaula A, Balzano S, Portincasa P, et al. Exposure assessment to radio frequency electromagnetic fields in occupational military scenarios: a review. Int J Environ Res Public Health. 2022;19(1):338.doi:10.3390/ijerph1901 0338.

[5] Dias S, Welton NJ, Sutton AJ, Ades AE. NICE DSU Technical Support Docu ment 2: A Generalised Linear Modelling Frame work for Pairwise and Network Meta-Analysis of Randomised Contro lled Trials. London: National Institute for Health and Care Excellence.

[6] European Parliament and Council. Directive/35/EU on the minimum health and safety requirements regar ding the exposure of workers to the risks arising from physical agents (electromagnetic fields). Official Journal of the European Union.

[7] Hareuveny R, Kavet R, Shachar A, Mar galiot M, Kheifets L. Occupational expo sures to radiofrequency fields: results of an Israeli national survey. J Radiol Prot. 35(2):429-445.doi:10.1088/0952-4746/ 35/ 2/ 29.

[8] Hu D, O'Connor AM, Wang C, Sargeant JM, Winder CB. How to conduct a Baye sian network meta-analysis. Front Vet Sci.2020;7:271.doi:10.3389/fvets.2020. 00 271.

[9] Hutton B, Salanti G, Caldwell DM, et al. The PRISMA extension statement for reporting of systematic reviews incor porating network meta-analyses of health care interventions: checklist and expla nations. Ann Intern Med.162(11): 777-784. doi:10.7326/M14-2385.

[10] Haddaway, N. R., et al. (2020). How to Conduct a Bayesian Network Meta-Analysis.

[11] Institute of Electrical and Electronics Engineers (IEEE). IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Elec tromagnetic Fields, 0 Hz to 300 GHz. IEEE Std C95.1- New York: IEEE.

[12] Institute of Electrical and Electronics Engineers (IEEE). IEEE Recommended Practice for Measurements and Compu tations of Electric, Magnetic, and Elec tromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 300 GHz. IEEE Std C95.3-2021. New York: IEEE; 2021.

[13] International Agency for Research on Cancer (IARC). Non-Ionizing Radiation, Part 2: Radiofrequency Electromag netic Fields. IARC Monographs on the Evalua tion of Carcinogenic Risks to Humans, Vol. 102. Lyon: IARC.

[14] International Commission on Non-Ionizing Radiation Protection (ICNIRP). Guidelines for limiting exposure to elec tromagnetic fields (100 kHzto300 GHz). Health Phys. 2020;118(5):483524. doi:10.1097/HP.000000000001210.

[15] InternationalTelecommunication Union (ITU). Recommendation ITU-T K.52: Guidance on Complying with Limits for Human Exposure to Electromagnetic Fields. Geneva: ITU; 2024.

[16] Jeschke P, Alteköster C, Hansson Mild K, et al. Protection of workers exposed to radiofrequency electromagnetic fields: a perspective on open questions in the context of the new ICNIRP 2020 guide lines. Front Public Health. 2022;10:875946.doi:10.3389/fpubh. 2022.875946.

[17] Liu, J., et al. (2022). Bayesian network meta-analysis methods for combining individual participant data and aggre gate data.

[18] Modenese A, Gobba F. Occupational exposure to electromagnetic fields and health surveillance according to the European Directive 2013/35/EU. Int J Environ Res Public Health. 2021; 18(4): 1730. doi:10.3390/ijerph18041730.

[19] National Institute for Occupational Safety and Health (NIOSH). Radio frequency (RF) Sealers and Heaters. DHHS (NIOSH) Publication No.80-107. Cincinnati: NIOSH..

[20] Nikolakopoulou A,Higgins JPT, Papa kon stantinou T, Chaimani A, Del Giovane C, Egger M, et al. CINeMA: an approach for assessing confidence in the results of a networkmeta-analy sis.PLoSMed.2020; 17(4): e1003082. doi:10.1371/journal.pmed.1003082.

[21] Occupational Safety and Health Admi nistration (OSHA). Elements of a Comprehensive RF Protection Program Role of RF Measurements Washington, DC: U.S. Department of Labor.

[22] Papakonstantinou T, Nikolakopoulou A, Higgins JPT, Egger M, Salanti G. CINeMA: software for semiautomated assessment of the confidence in the results of network meta-analysis. Camp bell Syst Rev. 2020; 16(1):e1080. doi:10.1002/cl2.1080.

[23] Salanti G, Ades AE, Ioannidis JPA. Graphical methods and numerical summaries for presenting results from multiple-treatment meta-analysis: an overview and tutorial. J Clin Epidemiol. 64(2):163-171.doi:10.1016/j.jclinepi. 120.010.03.016.

[24] Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR). Opinion on potential health effects of exposure to electromagnetic fields. Bioelec tromagnetics. 2015;36 (6):480-484. doi:10.1002/bem.21930.

[25] Sobiech J, Kieliszek J, Puta R, Bartczak D, Stankiewicz W. Occupa tional exposure to electromagnetic fields in the Polish Armed Forces. Int J Occup Med Environ Health.30(4):565-577.doi:10.13075/ijomeh.1896.00696.

[26] Stam R. Occupational exposure to radiofre quency electromagnetic fields. Ind Health. 2022;60(3):201-215. doi:10. 2486/indhealth.2021-0129.

[27] World Health Organization (WHO). Radiation: electromagnetic fields. Geneva: World Health Organization.