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Fuzzy Models for Evaluating the Effect of Radio Frequency Electromagnetic Fields on Health

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Abstract. Numerous studies of domestic and foreign researchers show that long-term exposure to electromagnetic fields (EMF) of artificial radio frequency range have negative effects on the human body. At the same time, if the effects of EMF of significant intensity are sufficiently well studied and regulated by the relevant sanitary norms and rules and state Standards, the harmful effects of low-intensity EMF are confirmed by many researchers, but there are practically no quantitative estimates of their impact on human health in combination with other exogenous and endogenous factors. In real conditions, the human body is often exposed to combined, combined and mixed EMF effects of various frequency ranges of different intensity, which cause a multiplicative effect, leading to an increased risk of occurrence and development of a number of socially significant diseases, especially when they are long-term exposure

1 Introduction

An analysis of the literature on assessing the impact of EMF on the human body has shown that it is mainly focused on statistical analysis of morbidity. Methods of synthesis of models for prediction, early and differential diagnosis of diseases provoked by the action of EMF of different modality in domestic and foreign studies are not given enough attention.

EMF occupies a large frequency band from 3 kHz to 300 GHz, which, having various mechanisms of interaction with the tissues of the human body, generate diverse responses of the body, leading to various pathological processes.

The synthesis of reliable models of decision-making about the state of people exposed to industrial radio frequency EMF is complicated by the fact that in addition to the studied risk factors, they are affected by numerous additional factors that often have an incomplete and unclear representation with an overlapping "poorly" defined class structure.

Nowadays the human body is exposed to combined, combined and mixed EMF effects of various frequency ranges of different intensity, which cause a multiplicative effect, leading to an increased risk of occurrence and development of diseases.

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In these conditions, taking into account the recommendations of the Department of biomedical engineering (BMI) of the Southwest State University (SWSU), it is advisable to use the methodology of hybrid fuzzy decision rules synthesis (MHFDRS), described in sufficient detail in [1, 2], to obtain "reliable" predictive and diagnostic decision rules.

2 The research methods

EMF of various intensities influence in different ways, generating thermal and specific processes in the human body. The nature of exposure from combined and combined radio frequency electromagnetic fields (RF EMF) in combination with other exogenous and endogenous risk factors significantly changes.

The analysis showed that in such conditions, the use of MHFDRS for the synthesis of appropriate predictive and diagnostic decision rules requires a creative approach that takes into account the specifics of the tasks being solved, specifying the ways and sequence of selecting particular models and their aggregation into the final decision-making models.

Taking into account the specifics of exposure to RF EMF in combination with other risk factors, a method for synthesizing mathematical models for predicting and diagnosing diseases provoked by exposure to RF EMF is proposed. It consists of the following main stages:

1. Formation of an expert group that is competent in the field of interaction of EMF with biological objects and has experience in the synthesis of hybrid fuzzy solvable rules for solving problems of forecasting and medical diagnostics with a poorly formalized data structure.

If necessary, the task of preparing experts for the synthesis of fuzzy decision rules is solved. The qualitative and quantitative composition of the group is selected in accordance with the requirements of qualimetry.

2. Determination of the frequency ranges f_i, the values of their energy exposure EE_I and individual (for each person) exposure time t_i, *I-th* frequency range during the entire contact time of the subject with the studied EMF.

When choosing frequency ranges, it is recommended to use the gradation accepted by Russian specialists (3-30 kHz (VLF), 30-300 kHz (LF), 300-3000 kHz (MF), 3-30MHz (HF), 30-300 MHz (VHF), 300-3000 MHz (UHF), 3-30 GHz (SHF), 30-300 (GHz)). Analysis of the literature data shows that similar biological effects of EMF interaction with biostructures are observed within these ranges.

When formulating the stages and elements of the synthesis of decisive rules, experts should take into account that the degree of influence of EMF on the human body depends significantly on its individual characteristics: psycho physiological individual portrait; presence of chronic diseases; age; adaptive reserve; functional state, etc. The effect of adaptation of the body to the harmful effects of EMF is well known. During the synthesis of fuzzy decision rules (FDR) you need to take into account the presence of resonance effects, especially for mixed and combined EMF and non-linear nature of risk cumulative, which is characterized in that at short contact even with high-energy EMFs, the risk of diseases is almost nonexistent, and with increasing contact time, the risk of occurrence and development of diseases of the nervous and immune systems, cardiovascular system and other organs and body systems is growing significantly nonlinear [3, 4].

Additionally (in addition to EMF), the risk factors that must be taken into account when synthesizing predictive and diagnostic IFS are individual risk factors (alcohol use, medication, heredity, etc.), environmental factors (geomagnetic fields, work and living in conditions of harmful production, etc.), ergonomic factors (working posture, microclimate, primary level of psycho emotional stress and fatigue, etc.).

According to the selected risk factors, the alphabet of the space of informative features and the alphabet of the studied classes of States are formed. When forming the analyzed classes of States, it is recommended to take into account that according to domestic and foreign scientists, the frequency range emitted by personal computers is characterized by the development of neurocircular dystonia and cardiovascular diseases. Long-term exposure to mobile phone EMF leads to headaches, decreased attention and memory, sleep disorders, fatigue, irritability, etc. In the zone of action of TV and radio towers, there is an increased risk of brain tumors and blood cancer; hormonal disorders; diseases of the Central nervous and cardiovascular systems; weakened immunity. Radar operators have hypotension, neurasthenia, increased fatigue, decreased concentration, General weakness, headaches, drowsiness, impotence [4–7].

Given the fact that a sufficiently powerful RF EMF determined by maximum permissible levels of known consequences, but for low-intensity EMFs indicated only a trend of possible diseases mainly on a qualitative level there are two different branches of synthesis of relevant decision rules.

It is reasonable to choose the mechanism of synthesis of fuzzy decision rules proposed in [7–9] for EMF of industrial frequency (50 Hz) as the basis for the synthesis of decision rules for EMF with 0.5 PDU and higher.

For low-intensity EMF, it is proposed to use a system of parameters with proven sensitivity to the response of the body to a long stay of a person in the range of electromagnetic fields of the radio frequency range.

For the EMF (range from 30 kHz to 300 MHz), the energy exposure of the electric (EE_E) and magnetic (of EE_N) fields exceeding 0.5 PDU, the basic element of decision rules is a function belonging to the investigated classes ω_l of states μ_{li} (z_{li}) with the basic variable z_{li} for frequency band i is determined by energy exposure of electric and magnetic components and the total time of exposure i-band on the human body.

In accordance with the recommendations [9–11], provided that the studied frequency ranges act on the subject at the same time t_v, the base variable for the class of diseases ω_l is proposed to be determined by the expression:

$$Z_l = f_l(Q) \cdot f_l^*(t_v), \tag{1}$$

where Q is the energy impact of exposure to EMF; $f_l(Q)$ is a function of the degree of influence of EMFs studied ranges on the emergence and development of diseases ω_l with domain of denition [0, ..., 1]; $f_l^*(t_v)$ is the function of the degree of influence of time of being surveyed under the influence of the investigated frequency range EMFs.

In accordance with the recommendations of the rules and state standards [9], if the subject is affected by EMF of the same frequency range f_i, then

$$Q = \frac{EE_{Ei}}{EE_{EiPDU}} + \frac{EE_{Ni}}{EE_{NiPDU}}, \tag{2}$$

where $EE_{Ei} = E_i^2 \cdot T$ is the energy exposure of the electric field for the frequency range f_i; E_i is the strength of the electric component of the EMF, T is time of exposure per shift in hours; $EE_{Ni} = N_i^2 \cdot T$ is the energy exposure of the magnetic field for the i-frequency range; N_i is the tension of the magnetic component of EMFs; EE_{EiPDU}, EE_{NiPDU} are corresponding maximum permissible levels.

When irradiated from several EMF sources operating in different frequency ranges, for which different PDUs are installed:

$$Q = \sum_i \left(\frac{EE_{Ei}}{EE_{EiPDU}} + \frac{EE_{Ni}}{EE_{NiPDU}} \right). \tag{3}$$

1. For EMF in the frequency range from 30 MHz to 300 GHz, the electrical exposure for expressions (2) and (3) is determined by the values of the energy flux density of the PPE. At the same time EE_E is replaced by $EE_{PPE}=PPE$ with "own" PDUs (EE_{PPEPDU}).

If several sources of different ranges "irradiate" the subject with different duration t_i, then different basic variables z_{li} are defined with the construction of "own" membership functions μ_{li} (z_{li}), which are aggregated into decisive rules of the type:

$$UEP_l = F_{lAg}\left[\mu_{li}\left(z_{li}\right)\right], \tag{4}$$

where F_{lAg} is the aggregation function for the analyzed frequency ranges; UEP_l is the confidence in the appearance and development of diseases ω_l by the electromagnetic component.

Given the possible resonant and nonlinear effects of different frequency ranges of EMF on the human body, it is advisable to determine the aggregation function from a training sample using a fuzzy modification of the method of group accounting for arguments [5].

In the absence of a training sample of sufficient size as an aggregator, it is advisable to check the applicability of E. Shortlif iterative expression, determining the parameters of membership functions in accordance with the recommendations [5]:

$$UEP_l\left(p+1\right) = UEP_l\left(p\right) + \mu_{l(i+1)} z_{l(i+1)}\left[1 - UEP_l\left(p\right)\right], \tag{5}$$

where p is the iteration number; $UEP_l\left(1\right) = \mu_{li}\left(z_{li}\right)$.

2. Concomitant risk factors related to ecology, ergonomics, and individual characteristics of the body are determined and, in accordance with the recommendations [10, 11], hybrid fuzzy decision models are synthesized for classes of states ω_l with the calculation of predictive and (or) diagnostic confidence UD_l .
3. The resulting partial decision rules are aggregated into final mathematical models

$$UF_l = FF_l\left(UEP_l, UD_l\right), \tag{6}$$

where FF_l are final aggregation functions.

In the alphabet of features of mathematical models UD_l it is advisable to use indicators of functional state, functional reserve, adaptive potential and protective functions of the body from the action of various harmful factors, including EMF.

4. For low-intensity EMF, the relationship between the parameters of the electromagnetic field and diseases arising from its action is more uncertain and unstable, which is determined by the weakening of interaction with biological structures, the work of adaptive mechanisms of the body, uneven intensity of exposure, often alternating pauses, for example, when using mobile communications.

Under these conditions, a model (5) is synthesized in the variant of selecting the type and parameters of membership functions by highly qualified experts in the absence of representative training samples. However, the low quality of decision making for rather low values of membership functions for EMF compensates increase of the number of additional informative features that characterize the individual characteristics of the organism with the inclusion of a measure of protective functions of an organism, determined, for example, in accordance with the recommendations of the works [7].

These papers provide a mathematical model for quantifying the level of protection UZ:

$$UZ = F_{UZ}\left(IFC, PLBP\right), \tag{7}$$

where IFC is the index of functional changes according to R. Baevsky; $PLBP$ is the level of protection determined by the energy characteristics of system-wide biologically active points (BAP).

Taking into account the indicator UZ, the membership function in expression (5) is replaced with a variable:

$$UEZ_{li+1} = \begin{cases} m_{l(i+1)}\left(z_{l(i+1)}\right) - UZ_{li}, & if \quad m_{l(i+1)}\left(z_{l(i+1)}\right) > UZ_{li}; \\ 0 \quad if \quad m_{l(i+1)}\left(z_{l(i+1)}\right) \le UZ_{li}. \end{cases}$$

For time and (or) space unstable RF EMF with badly defined classes of states, it is proposed to use fuzzy table models similar to the models, described in [9].

The model columns contain characteristics of the radiation source, such as classes of mobile phones, types of personal computers, types of routers, and so on.

The columns are used to determine the time of exposure. The elements of the table are confidence indicators UF_{lij} for the occurrence and development of disease ω_l for the EMF source with the number i for the time interval j.

For multiple sources with different time exposures confidence is determined by the UF_{lij} aggregation:

$$UEP_l = F_{UE}\left(UE_{lij}\right). \qquad (8)$$

Indicators UEP_l of expression (8) are aggregated with other exogenous and endogenous risk factors in the same way as recommendations [9–11].

5. In the conditions of reliably determined representative samples, it is recommended to use a number of EMF-sensitive indicators for rapid monitoring of the health status of people in the EMF zone. These indicators include the state of attention, memory, and thinking, as well as the dynamics of changes in the energy state of BAPS associated with the pathology of ω_l and system-wide BAPS.

This additional set of indicators can be used in decision-making models (6) to improve the quality of decisions made and to monitor the current state of the subjects in order to make decisions about possible correction of a number of human body functions.

3 Results

Using the described method of synthesis of hybrid fuzzy decision rules, the problem of obtaining mathematical models for predicting the appearance and development of diseases of the nervous system in people whose work is associated with long-term use of personal computers in combination with mobile phones was solved.

Taking into account the high uncertainty and non-stationary mode of operation of operators with mobile phones (MT) and personal computers (PC) to assess the impact of EMF of these technical means on the appearance and development of nervous diseases, experts selected a fuzzy table model as the base model, a fragment of which is presented in table 1.

Table 1. Assessment of confidence in the appearance and development of nervous diseases from the use of MT and PC.

A source EMF with connection type	Time (year)										
	1	2	3	4	5	6	7	8	9	10	>10
MT less than 10 connections	0	0	0	0	0	0	0	0	0	0	0
MT from 10 to 20 connections	0	0	0	0	0	0,05	0,05	0,1	0,1	0,15	0,2
MT from 20 to 40 connections	0	0	0	0,05	0,05	0,1	0,1	0,15	0,15	0,2	0,2
MT more than 40 connections	0	0,05	0,1	0,15	0,15	0,2	0,2	0,25	0,25	0,3	0,3
PC with a duration up to 1 hour	0	0	0	0	0	0	0	0	0	0,1	0,15
PC with a duration from 1 to 3 hours	0	0	0	0	0	0	0,05	0,1	0,15	0,2	0,25
PC with a duration from 3 to 5 hours	0	0	0	0	0	0,05	0,1	0,15	0,2	0,25	0,3
PC with a duration from 5 to 7 hours	0	0	0	0	0,05	0,1	0,15	0,2	0,25	0,3	0,35
PC with a duration from 7 to 9 hours	0	0	0	0,05	0,1	0,15	0,2	0,25	0,3	0,35	0,4
PC with a duration more than 9 hours	0	0	0,05	0,1	0,15	0,2	0,25	0,3	0,35	0,4	0,45

Table 1 shows the options for connecting to the MT connection per day and the duration of work with a PC connected to the wireless Internet per day.

The components of table 1 are aggregated using a private model of the form

$$UEP_N = UE_N\left(MT\right) + UE_N\left(PK\right) - UE_N\left(MK\right)\cdot UE_N\left(PK\right),$$

where $UE_N(MT)$, $UE_N(PK)$ is a confidence in the appearance and development of diseases of the nervous system from human contact with MT and PC, respectively.

The results of mathematical modeling and expert evaluation showed that for the most common working conditions, UEP_N is determined at the level of 0.42.

To increase the reliability of decisions in accordance with the recommendations [1, 4], it was decided to additionally use the energy characteristics of BAP and individual risk factors.

The synthesis of frequency decision rules using the energy characteristics of BAP is carried out in accordance with the recommendations of [9, 11]. Taking into account these recommendations for diseases of the nervous system, points P9, C5, V43, V60, R9 and MC7 should be used, including pairs of diagnostically significant points (DSP) {V60, R9} and {R7, MC7}.

In accordance with the recommendations a private mathematical model for determining confidence in the appearance and development of diseases of the nervous system has the form:

$$[(\delta R_{P9}\ AND\ \delta R_{V60})\ \text{OR}\ (\delta R_{R7}\ AND\ \delta R_{MC7}) \geq 20\%],\ \text{THEN}$$

$$\{UDB_H(j+1) = UDB_H(j) + \mu_H(\delta R_{j+1})[1 - UDB_H(j)]\}\ \text{OTHERWISE}\ (UDB_H = 0).$$

In [11] the following composition of informative signs was determined as the main individual risk factors for the class: taking medications that have a harmful effect on the nervous system (Ls); taking alcohol (AL); psycho emotional loads determined by the subjective feeling of the interviewee (PS); diseases of the nervous system in close relatives (Br).

In the same works, expressions are given for defining particular functions belonging to the class ω_N.

$$\mu_{PN}(Ls) = \begin{cases} 0{,}01Ls, & if \quad Ls < 25; \\ 0{,}25, & if \quad Ls \geq 25, \end{cases} \quad \mu_{PN}(AL) = \begin{cases} 0, & if \quad AL < 2; \\ 0{,}01AL - 0{,}02, & if \quad 2 \leq AL < 26; \\ 0{,}22, & if \quad AL \geq 26, \end{cases}$$

$$\mu_{PN}(PS) = \begin{cases} 0, & if \quad PS < 0{,}15; \\ 1{,}28PS - 0{,}19, & if \quad 0{,}15 \leq PS < 0{,}5; \\ 0{,}45, & if \quad PS \geq 0{,}5, \end{cases} \quad \mu_{PN}(Br) = \begin{cases} 0{,}05Br, & if \quad Br < 3; \\ 0{,}15, & if \quad Br = 3. \end{cases}$$

The selected group of experts suggested using as additional risk factors: hormonal disorders ($b1$); endocrine diseases ($b2$); coffee abuse ($b3$); chronic diseases of internal organs ($b4$); allergic diseases ($b5$); cervical osteochondrosis ($b6$); severe course of infectious diseases ($b7$); intoxication ($b8$); injuries ($b9$).

In the first approximation sufficient for estimation forecasts, the experts suggested that the given additional list of risk factors should be encoded in binary code (b_i =1 – there is a factor, bi =0 – there is no factor), and the total presence of the listed risk factors B should be determined by a simple sum of b_i, i.e.

$$B = \sum_i b_i .$$

In this case, according to the proposal, for this group of risk factors, confidence in the appearance and development of diseases is assessed by the function of belonging.

Assessment of confidence in the appearance and development of diseases of the nervous system for this group of signs is carried out using the expression:

$$UOG_N(q+1) = UOG_N(q) + \mu_{PN}(Q_{q+1})[1 - UOG_N(q)],$$
$$\text{where } UOG_N(1) = \mu_{PN}(LS);\ Q_2 = AL;\ Q_3 = PS;\ Q_4 = Br;\ Q_5 = B. \quad (9)$$

Confidence in the appearance and development of diseases of the nervous system for the obtained three components of confidence *UPH* in ω_N is determined by the expression:

$$UOH(q+1) = UPH(q) + Q_{q+1}[1 - UPH(q)],$$
$$\text{where } UPH(1) = Q_1 = \mathrm{UPH}_H;\ Q_2 = UDB_H;\ Q_3 = UOG_H. \quad (10)$$

As a result of mathematical modeling and expert evaluation, it was proved that the confidence in correct forecasting for the class ω_N exceeds the value of 0.85.

In the course of statistical control tests on representative control samples for two classes (ω_B - the subjects studied during 5 years of observation did not acquire diseases of the nervous system; ω_N - within 5 years, the subjects received diseases of the nervous system) it was found that the diagnostic specificity and sensitivity exceed the value of 0.87, which is a good practical result for predictive tasks.

4 Conclusion

The paper describes a method for synthesizing mathematical models for evaluating the impact of radio frequency electromagnetic fields on human health and provides fuzzy mathematical models for predicting the appearance and development of diseases of the nervous system in people exposed to electromagnetic fields of various modality in combination with other endogenous and endogenous risk factors. In the course of expert assessment and mathematical modeling, it is shown that confidence in the correct decision-making on the forecast of the development of diseases of the nervous system exceeds the value of 0.85, and in the presence of early stages-the value of 0.92, which allows us to recommend the results to the practice of specialized doctors.

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