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A Quantitative Index to Rank and Select Electromagnetic Shields in Radiofrequency and Microwave Radiation

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Abstract

Background: In electromagnetic shielding topics, the selection of suitable shields is an important subject and the lack of a specific ranking index for choosing protective shields causes problems in decision-making. Thus, this study proposes a quantitative index to rank and select electromagnetic shields in radiofrequency and microwave radiation.
Objectives: The objective of this study was to construct a simple quantitative index to rank and select electromagnetic shields in radiofrequency and microwave radiation.
Methods: A cross-sectional study was designed. In this study, the construction of the ranking index was carried out in four main stages including stabilizing the concept, analytical structure and variable selection, weighing and combination of variables, and validating the index. In this study, the average, minimum, maximum, and standard deviation of shielding effectiveness were considered the main phenomenon variables. Finally, the ranking index and ranking difference index were created as percentages to rank and select electromagnetic shields.
Results: In this study, a quantitative index was made as percentages called "Ranking Index" to rank and select the premier and preferable shield. Moreover, to indicate the difference in the shielding effectiveness of various shields, the "Difference Index" was made as percentages.
Conclusions: This study presented a simple quantitative index to rank electromagnetic shields. It could be used as a selection tool in radiation safety management. Moreover, this ranking index had a simple formula that could be calculated easily and quickly in excel software with high accuracy and low cost. In addition, it could be easily incorporated into a user-friendly tool for the ease of application. A case study of electromagnetic nanocomposite shields was conducted to use the Ranking Index, which showed its capability for ranking the shielding performance of studied electromagnetic shields. This index can create similar scientific literature to report the efficacy of electromagnetic shields and the selection of preferred shields in different research studies. It is suggested that future studies examine this quantitative index in other frequency ranges.

Keywords: Classification, Decision Making, Electromagnetic Radiation, Index, Microwave

1. Background

Radiofrequency and microwaves are parts of electromagnetic waves with a frequency of 3 kHz to 300 MHz with a variety of applications in military, medicine, telecommunication, etc. (1, 2). Therefore, many workers experience exposure to these radiations in various workplaces. Engineering control is the best safety approach to radio and microwave radiation protection to significantly reduce occupational exposure to radiation. So far, various studies have been carried out on electromagnetic shielding recommending occupational exposure control to protect workers against radiofrequency (3-7) and microwave (8, 9) radiation.

In recent years, there have also been many electromagnetic compatibility studies on nanocomposites for electromagnetic shielding (10-17). In electromagnetic shield topics, the selection of suitable shields is an important and interesting subject for experts in this field. The "check/control" is one of the steps to the implementation of occupational health and safety management systems in work environments. In this step, it is very important to use a precise and valid method to choose the optimal corrective action, especially when a variety of control measures exists. The lack of such a selection method/tool causes numerous problems such as wasting time and money and ineffectiveness of the applied control measures; the lack of a specific ranking index for choosing protective shields may also cause problems in making decisions in radiation safety management. Therefore, the existence of such a method can be useful in this context.

It is noticeable that some previous studies reported shield selection based on the shielding effectiveness (SE) range (18, 19) or maximum shielding effectiveness at a specific frequency (1, 2, 20, 21) and they did not use the determined selection or ranking method for electromagnetic shields. Furthermore, in other areas of occupational health and safety, there are various studies dealing with the selection and prioritization of some subjects by using multi-criteria decision-making techniques to rank or select the subjects. In this line, Janackovic et al. applied a systematic approach to the analysis of safety indicators. They used the expert evaluation method to select key occupational safety indicators and the fuzzy AHP method to rank them (22). Yarahmadi et al. prioritized the safety and health indicators based on the Fuzzy TOPSIS method with SMART criteria (3). Kamişli Öztürk et al. developed an integrated multi-criteria decision-making model for the selection of occupational safety employees (23). In another study, Changizi et al. used the hierarchical analysis process, Delphi techniques, and TOPSIS method to choose the best option of health, safety, and environmental criteria for ranking the Ahvaz urban parks (6). Asghari et al. determined and weighted the effective criteria in selecting a heat stress index using the Delphi technique and Fuzzy Analytic Hierarchy Process (FAHP) (5). Nadali Jelokhani et al. evaluated and ranked the safety risks of Isfahan municipality construction projects using taxonomic techniques and risk breakdown structure approach (7). In another study, Tabor applied the fuzzy TOPSIS method to assess and select a contractor from the point of view of occupational safety management (24). Also, in other topics of occupational safety, various safety indices were provided that focused on inherent safety assessment/design, hospital safety index, road and airline safety index, etc. (25-30). As shown by a literature review, we found no research on radiation safety index for ranking and selecting shields or barriers.

2. Objectives

The objective of this study was to construct a simple quantitative ranking index to rank and select electromagnetic shields in radiofrequency and microwave radiation. To the best of our knowledge and based on a literature review, there was no previous study on selection or ranking methods for electromagnetic shields.

3. Methods

In this cross-sectional study, the construction of the ranking index was carried out in four main stages, as follows (31, 32).

3.1. Stabilizing the Concept (Theoretical Framework)

The first step of the analysis consisted of defining the concept under investigation to make a more practical perspective. A precise and concise definition of the phenomenon is necessary for constructing a useful index (33). This stage provided a clear understanding and definition of the phenomenon to be measured (33-35). The shielding effectiveness was the original phenomenon to construct the quantitative index and rank electromagnetic shields. The concept of shielding effectiveness included a measure of the reduction of electromagnetic radiation at a specific frequency presented in decibel (dB). In other words, it is the ratio of incident field strength to transmitted field strength (36).

3.2. Analytical Structure and Variable Selection

In this very important step, single indicators were picked up based on several features, including analytical soundness, measurability, country coverage, relevance to the phenomenon being measured, and being related to each other (33-35). Thus, in a literature review, the variables related to the phenomenon of shielding effectiveness were extracted and confirmed by the experts. Finally, we found four variables including the arithmetic average, minimum, maximum, and standard deviation of shielding effectiveness to use as quantitative variables effective for constructing a ranking index.

3.3. Weighing and Combination of the Variables

The weights typically indicate the relative importance or extent of the contribution of specific items to the final index scores (37). Various approaches exist for weighting the index terms. In this research, the null method as a non-statistical method was used for weighting the variables. In null weighing, it is assumed that all variables are equal in weighting (31, 32). Due to the lack of similar studies in the literature, to determine the weights of variables, we assumed that the components of the index had the same importance in our research. Thus, for the composition of the variables, a null weighting method was used and the same weight was considered for all variables (31, 33-35).

During the steps of the index construction, the relationships among items were considered, with the anticipation of combining items into a single, one-dimensional constructed variable. By assigning scores to particular responses to an item, a single composite index was created through the basic summation of items (33-35). Using the combination of variables, two factors were provided to construct the ranking index. In this study, the first factor was called the partial value factor (V_p) that represented the ability of a shield in the shielding effectiveness. The second factor was called the ideal value factor (V_i), which represented the highest ability of a shield in the shielding effectiveness among all examined shields.

$$Partial\,Value\,Factor\ (vp) = \sum \left(SE_{(i,\ average)},\ SE_{(i,min)},\ SE_{(i,max)}\right) - SD_i \tag{1}$$

$$Ideal\,Value\,Factor\ (vi) = \sum \left(SE_{(a.average)}, SE_{(a,min)}, SE_{(a.max)}\right) - SD_{(a,min)} \tag{2}$$

Where: $SE_{(i,\ average)}$, the average of shielding effectiveness values for shield *i* in the measured frequency range; $SE_{(i,\ min)}$, the minimum shielding effectiveness value for shield *i* in the measured frequency range; $SE_{(i,\ max)}$, the maximum shielding effectiveness value for shield *i* in the measured frequency range; SD_i, the variation in shielding effectiveness values for shield *i* in the measured frequency range; $SE_{(a,\ average)}$, the greatest average of shielding effectiveness value among all the measured shields; $SE_{(a,\ min)}$, the greatest minimum shielding effectiveness value among all the measured shields; $SE_{(a,\ max)}$, the greatest maximum shielding effectiveness value among all the measured shields; $SD_{(a,\ min)}$, the least standard deviation of shielding effectiveness among all the measured shields.

As seen in Equation 3, from the ratio of partial value factor (V_p) to ideal value factor (V_i), an index is made called "Ranking Index" as percentages. The highest ranking index shows the highest shielding efficacy. Therefore, the shield with the highest ranking index would be the premier and preferable shield.

$$Ranking\ Index\ (RI\ \%) = \frac{V_p}{V_i} \times 100 \tag{3}$$

To indicate the intensity and weakness of the performance of each shield relative to the preferred shield, the "Difference Index" was made as percentages, as shown in Equation 4.

$$Ranking\ Difference\ Index\ (\%) = RI_p\% - RI_i\% \tag{4}$$

Where: $RI_p\%$, ranking index for the premier shield; $RI_i\%$, ranking index for each shield.

3.4. Validating the Index

This step involved index validation. The construct validity is probably most difficult to establish, as it deals with what the construct ultimately measures. Many variables that are easily "observable" (such as those in our research) do not present any formidable difficulties in establishing construct validity but subjective evaluations could be more challenging. Item analysis provides a means of testing for internal validation. In other words, the index is examined across item responses that comprise it (37). For this purpose, item analysis was performed to provide the testing for internal validation.

3.5. Case Study

In this study, a case study was conducted to examine the Ranking Index and Ranking Difference Index using a shielding effectiveness dataset for single and double nanocomposite shields (including 22 nanocomposite electromagnetic shields) in microwave radiation (X-band frequency range) that were made in previous studies and their physical electromagnetic properties were directly collected by a vector network analyzer (31, 33).

4. Results

In this study, a quantitative index was made called the "Ranking Index" expressed as percentages to determine the premier and preferable shield (Equation 3). Moreover, to indicate the difference in the shielding effectiveness of various shields, the "Difference Index" was made and expressed as percentages (Equation 4).

It is considerable that the testing process was repeated frequently and the same results were obtained in this study. The results of the case study of nanocomposite electromagnetic shields are shown in Tables 1 and 2. Table 1 represents the characterization of 22 nanocomposite electromagnetic shields (12 single-layer and 10 double-layer shields) that had been provided in previous studies (12, 14) to use for examining the ranking indices. The ranking of electromagnetic shields in this table was based on the average of shielding effectiveness values. This table indicates that the 7% - 4 mm and 5% - 2 mm nanocomposite shields (were two of the 22 nanocomposite shields previously prepared) with 66.72% and 36.24% average shielding effectiveness values had the most and least shielding effectiveness, respectively, among all the studied shields. Also, as seen in this table, the maximum (84.18%) and minimum (16.73%) shielding effectiveness values were achieved by 11% - 6 mm and 5% - 2 mm shields, respectively, among all the shields.

Table 2 characterizes the partial value factor, ideal value factor, ranking index, and difference ranking index for studying shields. As shown in Table 2, all considered shields were sorted based on a novel ranking index as presented in Equation 3. According to this ranking index, the 7% - 4 mm nano-electromagnetic shield was the preferred shield that took the first rank in the ranking table in this study with ideal value factor, partial value factor, and ranking index of 191.752, 181.060, and 94.424%, respectively (Equations 1 and 2). The 11% - 4 mm and 5% - 4 mm shields with ranking indices of 91.177% and 90.818%, respectively, were in the next ranking places. Also, the ranking

Table 1. Summarized Characterization of Shielding Effectiveness for Studied Shields

Shield[a]	Number of Layers	$SE\%_{Average}$	SD (%)	$SE\%_{Min}$	$SE\%_{Max}$
5% - 2 mm	Single	36.24	12.10	16.73	51.42
7% - 2 mm	Single	45.97	13.50	27.47	59.6
9% - 2 mm	Single	40.96	12.30	23.27	62.63
11% - 2 mm	Single	46.8	13.50	29.74	60.39
5% - 4 mm	Single	64.12	18.90	50.2	78.73
7% - 4 mm	Single	66.72	19.09	52.95	80.48
9% - 4 mm	Single	59.44	16.44	44.63	74
11% - 4 mm	Single	65.38	21.48	49.63	81.3
5% - 6 mm	Single	64.18	27.56	42.72	83.57
7% - 6 mm	Single	64.52	24.32	46.9	82.32
9% - 6 mm	Single	64.43	25.36	45.6	82.39
11% - 6 mm	Single	59.93	31.13	32.11	84.18
9% - 11%	Double	44.31	22.55	12.5	69.7
7% - 11%	Double	45.25	25.53	14.35	73.58
7% - 9%	Double	47.99	18.34	21.1	65.38
5% - 11%	Double	51.42	34.08	27.23	81.5
5% - 9%	Double	47	24.66	13.6	73.24
5% - 7%	Double	47.96	25.36	19.4	74.5
11% - R	Double	47.87	18.90	22.64	65.87
9% - R	Double	52.48	18.72	33.7	70.58
7% - R	Double	52.51	19.09	33.04	71.16
5% - R	Double	47.03	19.65	15.52	66.27

[a]The single-layer shields were named by two features that were thickness and filler loading (wt.%). For example, the shield with 2 mm thickness and 5 wt.% nickel oxide loading content was named 5% - 2 mm. The double-layer shields were named based on filler loading (wt.%) in the first and second layers. For example, the double-layer shield with 9 wt.% and 11 wt.% filler loading in the first and second layers, respectively, was named as 9% - 11%.

difference index for them was 3.247% and 3.606%, respectively. Finally, the 5% - 2 mm shield, as the weakest electromagnetic shield in this study, was placed at the bottom of this table with a 48.131% ranking index. It is noticeable that among nano-electromagnetic double-layer shields, the 9% - R shield with a 71.991% ranking index was the premier double-layer shield that was seen in the ninth ranking place in Table 2.

5. Discussion

Today, electromagnetic shield selection is a challenging task for designers due to non-ionizing radiation safety. Choosing the right electromagnetic shields in radiofrequency and microwave radiation plays an important role in numerous engineering applications because an inappropriate selection of shields can significantly affect the performance of the final radiation control measures. This paper aimed to propose a tool called the quantitative index for the classification of electromagnetic shields in radiofrequency and microwave radiation.

As a result of a literature review, it was shown that there was no similar study about electromagnetic or radiation shield and it was a limitation in this work. But, several techniques have been conducted to rank or select the issues in various occupational safety and health topics, such as AHP and TOPSIS (6, 7, 22, 24, 38). The Analytic Hierarchy Process (AHP) is one of the most widely used multi-attribute decision-making (MADM) methods that be used in many different fields as a multi-attribute decision analysis tool with multiple alternatives and criteria. The Fuzzy AHP methods are systematic approaches to the alternative selection and justification problem by using the concepts of Fuzzy set theory (39). In most recent studies, the selection was a complex problem, in which many qualitative attributes (subjective research) must be considered. These kinds of attributes make the evaluation process hard and

Table 2. Summarized Characterization of Value Factors and Ranking Index for Studied Shields

Ranking Place	Shield Name	Number of Layers	Ranking Index (%)	Ranking Difference Index (%)	Partial Value Factor	Ideal Value Factor	$SE\%_{Average}$	SD (%)	$SE\%_{Min}$	$SE\%_{Max}$
1	7% - 4 mm	Single	94.424	0.000	181.060	191.752	66.72	19.09	52.95	80.48
2	11% - 4 mm	Single	91.177	3.247	174.834	191.752	65.38	21.48	49.63	81.3
3	5% - 4 mm	Single	90.818	3.606	174.146	191.752	64.12	18.90	50.2	78.73
4	7% - 6 mm	Single	88.355	6.069	169.423	191.752	64.52	24.32	46.9	82.32
5	9% - 6 mm	Single	87.125	7.299	167.065	191.752	64.43	25.36	45.6	82.39
6	5% - 6 mm	Single	84.960	9.464	162.914	191.752	64.18	27.56	42.72	83.57
7	9% - 4 mm	Single	84.291	10.133	161.630	191.752	59.44	16.44	44.63	74
8	11% - 6 mm	Single	75.663	18.761	145.085	191.752	59.93	31.13	32.11	84.18
9	9% - R	Double	71.991	22.433	138.044	191.752	52.48	18.72	33.7	70.58
10	7% - R	Double	71.770	22.654	137.620	191.752	52.51	19.09	33.04	71.16
11	5% - 11%	Double	65.745	28.679	126.068	191.752	51.42	34.08	27.23	81.5
12	11% - 2 mm	Single	64.368	30.056	123.427	191.752	46.8	13.50	29.74	60.39
13	7% - 2 mm	Single	62.339	32.085	119.537	191.752	45.97	13.50	27.47	59.6
14	11% - R	Double	61.265	33.159	117.477	191.752	47.87	18.90	22.64	65.87
15	5% - 7%	Double	60.758	33.666	116.505	191.752	47.96	25.36	19.4	74.5
16	7% - 9%	Double	60.562	33.862	116.129	191.752	47.99	18.34	21.1	65.38
17	9% - 2 mm	Single	59.744	34.680	114.560	191.752	40.96	12.30	23.27	62.63
18	5% - 9%	Double	56.936	37.488	109.176	191.752	47	24.66	13.6	73.24
19	5% - R	Double	56.934	37.490	109.173	191.752	47.03	19.65	15.52	66.27
20	7% - 11%	Double	56.142	38.282	107.654	191.752	45.25	25.53	14.35	73.58
21	9% - 11%	Double	54.214	40.210	103.957	191.752	44.31	22.55	12.5	69.7
22	5% - 2 mm	Single	48.131	46.293	92.292	191.752	36.24	12.10	16.73	51.42

vague. Thus, the hierarchy was used mostly in these studies (40, 41).

Instead, objective indicators are used in observational and measurable studies that contain the physical quantities. These indicators are mostly quantitative (31). Many observational and measurable studies were performed in occupational safety and health that led to index construction to rank and select the points. In this regard, it can refer to studies that focused on hospital safety index (27), integrated inherently safety index (26, 30), road safety index (28), airline safety index (25) for chemical process design considering risk analysis and controllability (42), and inherent safety assessment by process stream characteristic index (PSCI) (43). But, the related studies about radiation safety or ranking index for electromagnetic shields were not found.

The current work proposed a quantitative index on electromagnetic quantities to rank and select the electromagnetic shields. This index included several aspects that are important in choosing the best shield for electromagnetic shielding such as average, minimum, maximum, and standard deviation of shielding effectiveness.

In our research, the quantitative index was implemented on the single and double-layer electromagnetic shields that had been previously constructed (Tables 1 and 2). As shown in Table 1, the 7% - 4 mm, 11% - 4 mm, and 5% - 4 mm shields were the first to third premier and preferred shields for microwave radiation protection in this study based on only the average of shielding effectiveness.

Before this, some research such as studies by Al-Ghamdi and Qing et al. reported the premier shield based only on the better average or range of shielding effectiveness (from minimum to maximum value of shielding effectiveness) (18, 19). Thus, in these studies, shielding effectiveness variations and average, minimum, and maximum values of shielding effectiveness were not taken into account. In addition, recent studies referred to the highest shielding effectiveness value to determine the premier shield. In this line, Fan et al., Mazov et al., Shah et al., and Hou et al. selected shields based on maximum shielding effectiveness value (1, 2, 20, 21). If these criteria were used to select the premier shield, the 11% - 6 mm, 5% - 6 mm, and 9% - 6 mm shields with 84.18%, 83.57%, and 82.39% maximum shielding effectiveness, respectively, were the first to third preferable shields. Therefore, the premier shield was evaluated and introduced based on only one parameter in those kinds of studies. In the current study, for the first time, a novel quantitative index was constructed to simply, quickly, and accurately rank electromagnetic shields based on four quantitative criteria including average, minimum, maximum, and standard deviation of shielding effectiveness values. Using this ranking tool, the 7% - 4 mm nano-electromagnetic shield was the premier shield that took the first rank in the ranking table in this study (Table 2).

A comparison of the quantitative ranking index between single and double-layer shields showed that the ranking index was often more in single-layer shields than in double-layer shields. Thus, the double-layer shields were not optimum shields for radiation protection in this study (Table 2). It is noticeable that using this ranking index, the arrangement of the first to third premier shields changed to 7% - 4 mm, 11% - 4 mm, and 7% - 6 mm shields, respectively.

In this study, using quantitative variables, a numerical ranking index was made to rank electromagnetic shields and compare them quickly and easily to create a selection tool in radiation safety management. It also helps create similar scientific literature to select the premier shields in different research studies. Other characteristics of this index are validity and reliability. The validity (most known as content validity) refers to the extent to which a measure represents facets of a given construct. Content validity concerns determining the suitability of the segmentation variable for a clearly specified domain of interest (37, 44). In our research, this was done by referring to the literature and trusting professionals and experts. In this study, variables selected for constructing the index were extracted from the concept of shielding effectiveness, which were directly measured and used to make a valid and reliable index (31, 32). This index involves the related variables that measured shielding effectiveness. Moreover, each item was empirically related to one another when measuring the shielding effectiveness (31, 32).

As far as we know, in statistics and psychometrics, reliability is the overall consistency of a measure. A measure has high reliability if it produces similar results under consistent conditions (37). In our research, the testing process was repeated frequently with a group of shields and the same results were obtained each time. Therefore, the index was highly reliable with accurate, reproducible, and consistent results from one testing occasion to another.

In this work, the quantitative index was developed with a simple formula that could be calculated easily and quickly in excel software with high accuracy, low cost, and minimal time waste. In addition, as the results in Table 2 showed, this quantitative ranking index with a highly distinctive power could determine the differences in shielding effectiveness. Using this index, we can assess and compare the efficacy of different shields in radiofrequency and microwave bands. Creating comparative safety performance is an excellent point for the quantitative index that helps understand the relative safety strengths and weaknesses in terms of manageable safety attributes, and identify functional areas for safety improvement (25).

Also, this index can be used for radiation safety planning and policy-making. Furthermore, identifying the preferred shields in existing conditions and planning for the production and development of shields are other advantages of this index. It is suggested that future studies examine this quantitative ranking index in other electromagnetic frequencies.

5.1. Conclusions

Choosing the right electromagnetic shields in radiofrequency and microwave radiation plays an important role in radiation safety engineering. This study presented a novel quantitative ranking index to simply and easily rank electromagnetic shields numerically and quickly with minimal time and cost waste without any complex software in radiofrequency and microwave radiation. The present quantitative index could be used as a selection and compassion tool to determine the premier shield field. Also, other intentions like the comparison of various electromagnetic shields, improvement and development of electromagnetic shields, and radiation safety planning would be achieved. Moreover, the application of this index could create the same literature for informing and clarifying the ranking of electromagnetic shields with a quantitative tool. This index includes several aspects that are important in choosing the best shield for electromagnetic shielding, such as average, minimum, maximum, and standard deviation of shielding effectiveness. In this study, the selected variables in constructing the index were extracted from the concept of shielding effectiveness. In addition, the testing process was repeated frequently and the same results were obtained each time. Therefore, the presented quantitative index was reliable and valid.

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Footnotes

Authors' Contribution: Study concept and design, analysis and interpretation of data, drafting of the manuscript, and critical revision of the manuscript for important intellectual content: Vida Zaroushani; administrative support and critical revision of the manuscript for important intellectual content: Farahnaz Khajehnasiri.

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