Inductively Coupled Electrical Stimulation - Part 5: How many types of PEMF are there? A model and Excel Calculator

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To intelligently study anything, the first step is to intelligently define exactly what it is that you are studying. This has been a perennial challenge for the field of PEMF research. The most basic question in the field of PEMF research is: exactly what is PEMF, and if it is more than one thing, how many different things is it?

At the simplest level, PEMF is exactly what it stands for: Pulsed Electro-Magnetic Fields. But in common usage, it is more nuanced than that. This is a term not used by physicists, for example, to describe the pulses that are observed emanating from outer space. These are described by detailed spectral analysis of the electromagnetic emission being studied, but physicists do not generally use the generic term “PEMF”. It is also not a term used by electrical engineers to describe the electromagnetic fields emanating as a byproduct of the clocking of digital electronics or control of motors, even though, technically, these could be called pulsed electro-magnetic fields. The term and abbreviation “PEMF” is used almost exclusively to describe a specific type of electro-magnetism that is known or believed to have beneficial or therapeutic effects when applied to living systems.

In this study, we first address the fundamental weakness of the ubiquitous question “Does PEMF work?”

We then begin by re-framing the question with clearly defined terminology. Then we finish by presenting a model for dividing PEMF into tractable subsets based on quantifiable PEMF parameters. A spreadsheet is developed to model and calculate the total number of all possible forms of well-defined PEMF that could be tested for biological effects. The spreadsheet is available for use to aid research in this area.

Using default parameters selected by the author, it is concluded that there are about 1 quadrillion different variations of PEMF, which far exceeds the number of identified and theorized chemical species in the known universe. While this number by itself is intractable, when modeled in detail it does allow the variations of PEMF to be estimated and organized in a way that it becomes possible to approach the problem of the scope of PEMF within a tractable experimental or regulatory framework.

Citation

Dennis R. (2021). Inductively Coupled Electrical Stimulation - Part 5: How many types of PEMF are there? A model and Excel Calculator; 4(2):1-10. https://doi.org/10.37714/josam.v2i4.67.

Introduction and Rationale

The question of whether or not PEMF actually works has been a perennial open issue in biomedical research for more than a half century. It seems like the answer should be simple enough: YES or NO. But it turns out that the lack of an answer is not the problem, it is how people have been looking at the question. To frame this question correctly, it is necessary to take a big step back, adjust perspective with some light humor, and re-think the way it has been asked. We will need to reformulate the question from the very beginning, by pulling back the many misleading layers that have accreted over the decades, because the countless attempts to re-answer the basic vague question have not moved the field of PEMF forward appreciably for many decades. We need to unwind the question from decades of misunderstanding and misrepresentation, and reformulate the question about PEMF using well-defined terms.

Grasping Large Numbers:

As the joke goes, an aide briefed President George W. Bush one morning, and included a report that three Brazilian soldiers had been killed at their Western border by Sendero Luminoso terrorists from Peru. The President replied “That’s terrible. I mean that’s a *whole lot*!”. Then, leaning toward another aide, he whispered, “How many is a *brazillion*?”

This is humorous because it shows a basic human weakness: the inability to grasp truly large numbers. “Brazillion” is a phonetic play on make-believe words such as “gazillion”, “jillion”, and “zillion”, each of which, precisely defined, are understood to mean “a ridiculously large number”.

Big numbers are simply hard to grasp. In a meeting with the defense department during the same administration, there was a discussion about the progress of space-based laser systems. The technical analyst reported that the new lasers needed a power output “on the level of 10^{12} [that is, ten to the 12^{th} power], but at best, we have achieved 10^{6}.” A high-level official chortled blithely, “Well, I guess we’re half way there!”

One should note that 10^{6} is not half way to 10^{12}, it is one millionth of the way to 10^{12}. It is only 0.0001% of the way. Big numbers are hard for most people to grasp.

Any consideration of PEMF involves big numbers. Really, really, really big numbers. That is the first half of the challenge when trying to think intelligently about PEMF. The second half is that we do not have a firm definition of exactly what PEMF *is*.

When faced with a question that is not well defined, so much so that it is not even known exactly what is being talked about, and when this unclear definition is combined with the fact that it involves incomprehensively enormous numbers, then one might understandably conclude that the problem is unsolvable. But problems of enormous numbers combined with vague terminology can be whittled down to a manageable size when they are looked at in a logical, systematic way.

It is helpful to borrow from other areas of science that have grappled successfully with this issue.

Take for example the Drake Equation. When faced with the seemingly impossible question of determining whether or not our galaxy contained extraterrestrial intelligent life, in 1961 the astronomer Frank Drake reformulated the question to help define what specific questions needed to be asked, and answered, before we could begin to estimate the number of intelligent civilizations outside the earth. First, he started with a simple definition: “intelligent life” means some form of life that can communicate across the vast distances of space. Therefore, he reasoned, it must be some form of technological civilization. By defining it that way, he narrowed the search significantly. For example, we were no longer asking about simple lifeforms, like bacteria. But we were also not talking about intelligent but non-technological forms of life, like dolphins or monkeys. By definition we would only look for distant life that could reach out and communicate across empty space: communicative technological civilizations.

Then he wrestled with the big numbers. Starting with estimates of the numbers of stars in the Milky Way galaxy (a number known to be larger than 100,000,000,000, i.e., 100 Billion), the next logical questions began to take form: how many planets are there around the average star? How many of these planets can support life, and so forth for a total of seven different factors that are multiplied together: some are very large, others are very small probabilities. When you take an educated guess at all of the factors and probabilities, it becomes possible to guess the number of technological civilizations in our galaxy. Over the years, many estimates have emerged. These tend to range from about 10 to 10,000.

But more importantly, the Drake Equation has played a key role in getting scientists to ask the right questions, which has led to the development of new telescopes and satellites to probe the universe to find those answers. As a result, scientific progress in the field of astronomy and the search for life since the Drake Equation has been astonishing. And it all began with clear definitions and numbers, and carefully reformulated questions.

So, it turns out that it is possible to start with unanswerable questions using vague definitions and huge numbers and distill it all down to an answerable question using few, manageable sized numbers and clear definitions for all of the key terms. This means it is possible to begin to make progress toward an answer. It requires that we (1) establish a few clear definitions, and (2) begin to assign numbers to the things we have defined, then (3) ask the right questions about those things.

This method can be transported to the scientific research field of PEMF. The vague question is usually presented as “Does PEMF work?” Looking closely, this question is about 2/3 vague and as such, is probably unanswerable. What do we mean, exactly, by the terms “PEMF” and “work”? A huge body of literature has embarked on the endeavor to answer this vague question without first defining the terms within the question itself carefully. The result has been more than a thousand papers published over a period of more than 6 decades without getting a clear YES or NO answer. We cannot just keep doing the same things, building upon this work, and expect to get a clear answer. We have to start at the beginning.

So, let’s begin with definitions for two terms: *PEMF* and *work*

First, we must define what we mean by the word “work”. In the context of health and medicine, it means that the thing in question has a biological benefit. It improves health, well-being, growth, injury recovery, reduction of disease burden, etc. We might go further to say that, in order to “work”, PEMF (or any other form of treatment) must produce a repeatable, measurable benefit to a living system. Some things are hard to measure with an actual number, such as “well-being”, others are much easier, such as “did the bone heal?” So, in order to determine whether PEMF “works”, it helps to study the observable effects on biological systems that are known to be beneficial and can be measured. Biomedical scientists are pretty good at this already, so that is not the problem. But we need to be clear and precise with the terminology when asking scientific questions.

Second, you would think that the term *PEMF* is well-defined technically, but it is not. Therefore, we will propose a definition: PEMF (pulsed electro-magnetic fields) are *those specific electro-magnetic patterns and waveforms that can be observed to have repeatable, measurable, statistically significant biological effects*. For our purposes, we will define that PEMF must be *clinically beneficial electromagnetic pulses,* which means that the resulting effect must be shown to confer clinical benefit. Therefore, electro-magnetism that is known to be harmful, such as hard gamma rays and noise from electro-magnetic interference (EMI) are excluded. We would also exclude pulses that are used to ablate or destroy tissues, which are sometimes used clinically and surgically, because while the ultimate effect may be desirable, the direct effect on tissues is destructive. We might also specify that PEMF is not to include ionizing electromagnetism, or frequencies in the spectrum of *light* (visible, UV, infra-red), which means that our definition of PEMF includes only those frequencies below about 300 GHz (extremely high frequency microwaves), but not higher. Finally, we must (unfortunately) be clear that PEMF only includes those types of electromagnetism that are *real*. It is unfortunate, but because of the widespread fraud and pseudo-science in the marketing of PEMF, we must explicitly exclude make-believe nonsense such as *scalar waves* [1].

We must also consider that electromagnetism includes combinations of frequencies, not just single unique or monotonic frequencies. A common example would be purple light, which is a combination of red and blue. Similar combinations could be made at lower frequencies, and these would also be potential candidates that would comply with our definition of PEMF. It is important to note that any electromagnetic wave or pulse that is not perfectly sinusoidal and continuous must contain multiple frequencies, and in reality, combinations of frequencies are much more common than single pure frequencies. This is true generally both for naturally occurring and artificial electromagnetism.

This means that PEMF could be comprised of any combination of frequencies of electromagnetism from 0 Hz up to about 300,000,000,000 Hz. Electromagnetic effects at different frequencies that fall within in this range are known to have different biological effects. That means that PEMF could end up being a lot of different things, depending on the combination of frequencies, not to mention other parameters of the electromagnetism being tested.

Now that we have a clearer definition of “PEMF” and “work”, we might reformulate the initial question to be:

Do specific types of PEMF have repeatable, measurable, beneficial biological effects?

This is now an answerable question. It can be transformed directly into a series of *testable hypothesis* by sharply defining the exact type of PEMF to be tested, and the exact biological effect to be observed and measured.

To make this question experimentally tractable, we need to narrow it down to specific details:

1. Exactly what type of PEMF is to be tested?
2. Exactly what biological effect is to be observed and measured?

Usually, it is best to limit a biological experiment to one type of sample, for example, a human bone with a certain kind of injury, or another type of tissue from one type of animal with one type of well-defined injury. This makes the resulting clinical generalizations more difficult, but it makes the experiment itself practical and possible to do, and statistically manageable.

All of this leaves one final loose end: exactly what type of PEMF should be used in the experiment? That is a difficult choice that is usually ignored by researchers. They simply tend to use whatever they have available or what has been done before. But we know there are many types of PEMF. It is important to define exactly what type will be tested, otherwise it is impossible to conclude anything from the experiment. Most people do not have an intuitive sense for this because most people still think of PEMF as “one thing”. But it can be many different things. In this respect, the term “PEMF” is like the word “chemicals”. If you plan to do an experiment on the biological effects of a “chemical”, the first thing you need to do is to define, precisely, which chemical you will test.

Water? Testosterone? Plutonium? These are all chemicals, but each will have very different biological effects. The same is true for PEMF, and therefore the exact type of PEMF needs to be clearly defined before any meaningful experiment can be done.

This brings us to the most important question. This must be addressed before formulating any experiment directed toward the question, broadly stated, about the efficacy of PEMF:

How many *different* types of PEMF are there?

With this question, we need one additional definition: the exact meaning of the word “different”. Is the number 10 different from the number 11, or 10.1, or 9.999999999999? Mathematically, yes. Biologically, it depends. More than a decade ago, I asked the FDA for an opinion on exactly how different a frequency had to be so that it would be considered “different” from a regulatory perspective. Specifically, we asked if 10 Hz was the same as 11 Hz. The official answer was YES. No explanation, just YES. We then asked if 10 Hz was different from 10.1 Hz. The answer was again YES. We then asked how small of a difference would be considered a difference. The answer was that *any* difference would trigger regulatory testing and recertification. Conclusion: according to the FDA, in terms of PEMF frequency, any change at all would be considered a different form of PEMF, subject to new requirements for testing and approval for safety and efficacy.

Based on initial studies conducted at NASA [2], I have argued elsewhere [3,4] that the key PEMF parameters are dB/dt and pulse width (for a very broad band of frequencies), and that dosage is a function of intensity (amplitude) and total number of pulses [5,6]. However, the FDA still subscribes to the “magical frequency” hypotheses of PEMF, so any changes to “frequency” are equivalent, in regulatory terms, to changes in the regulated device itself. This is essentially similar to the assertion that any changes to the molecule of a drug are changes to the drug itself. *Prima facie*this is reasonable, at least for molecules, but does it make sense for PEMF “frequencies”?

Here is the problem: between any two finite numbers there are an infinite number of different numbers.

Therefore, there would be an infinite number of different frequencies in the range that we define as acceptable for PEMF. So, it only makes sense to consider differences that we can measure, not mathematical abstractions. Electromagnetic frequencies can be accurately measured to at least five significant figures, but not infinitely. That means we can reduce the number of possible *different* frequencies down from infinity to a finite number, for any range of frequencies. It is at this point that we can begin to calculate the number of possible different variations of PEMF.

Methods

A spreadsheet in Excel [link] was created to calculate the number of all possible forms or variations of parameters of therapeutic PEMF. The total was calculated as the total number for all possible combinations of all parameters that could be differentiated using Boolean Operators or quantified within a well-defined range.

The spreadsheet then includes the ability to input different ranges for each parameter, whether or not to include some parameters (such as different waveforms), and the resolution for each quantitative measure of each parameter, that is, how much of a change in any given parameter constitutes a “different” form of PEMF, being mindful that the advice from the FDA was that *any change* in any parameter makes PEMF different from a regulatory standpoint.

The resulting spreadsheet is available [link] for inspection and comment. Each parameter can be varied to see the effect on the total number of possible forms of PEMF.

Variation of Parameters

For each parameter, either it is included by Boolean Operator (AND, NOT), or it is a measurable variable with a range (R) defined on a closed interval by a minimum (min) and a maximum (max), as well as an increment for each parameter (tolerance) that indicates the smallest difference in value that would be taken to indicate that the PEMF is “different” from the adjacent quantities. For example, if the smallest increment were set to 1.0, then we would define PEMF using 11.0 Hz to be different from PEMF using 10.0 Hz. However, 10.9 would not be considered different from 10.0 because the change in value is not >= the defined increment. The increment can be defined as an absolute number (Δ), but for this model the increment is generally defined as a percent change of the value of the parameter (Δ%), in which case it is indicated on the spreadsheet by “% tolerance”, using the 1-2-5 tolerance sequence common in the definition of values such as electronic components (e.g. resistors). The desired tolerance is selected by pull-down menu for each parameter.

Each waveform parameter is defined in this way, including amplitude (peak Gauss), frequency (pulses per second), percent duty cycle, percent rise time, percent fall time, and then a definition of pulse train bursts, if those are to be tabulated, defined as number of pulses per burst of pulses, and delay time between bursts. The final parameter to be considered is the treatment time, which is also a regulated parameter for PEMF dosage, for example when applied in the form of TMS (transcranial magnetic stimulation) for the treatment of depression and PTSD. For flexibility of the model, this parameter can be excluded from or included into the total tabulation.

Other waveform parameters may be included or excluded by Boolean Operation, including the consideration of which general classification of waveforms to include (sine, square, triangle, trapezoidal, continuous or periodic), waveform symmetry (for triangle and trapezoidal waves), bipolarity versus unipolarity, the use of leading doublets or triplet pulses as these were common in classical muscle and nerve physiology experiments, and the ability to mix parameters by combining different waveforms in a series of pulses, such as triangle waves and square waves. The last is calculated by simple factorial of the number of parameters you wish to mix in the signal, for example, to accommodate the combination of different frequencies as well as different waveform shapes in one PEMF signal.

For waveforms with leading and trailing edges (trapezoidal and triangle), more detailed specification of the parameters is included, to enable the calculation of the first time derivative of the magnetic field ($d\mathbf{B}/dt$) so that accurate calculations of the inductive energy transfer could be subsequently made, and standards set for PEMF systems that are based on inductive energy transduction, such as ICES®-PEMF. The use of these parameters to define the biologically effective range and dose-response characteristics of trapezoidal wave PEMF has been demonstrated and described elsewhere [3-7].

Default values are given for each of the parameters, tolerances, and Boolean Operators, and the spreadsheet is automatically recalculated upon the change of any value.

Results

The spreadsheet displays the final result at the top: total number of possible distinct variations of PEMF protocols.

Using default values set by the author to reflect his opinion of reasonable initial values as well as those commonly published in the PEMF literature, the result is that there are 1,164,819,418,495,920 different ways to apply PEMF by varying the waveform shape, frequency, amplitude, and other parameters Figure 1.

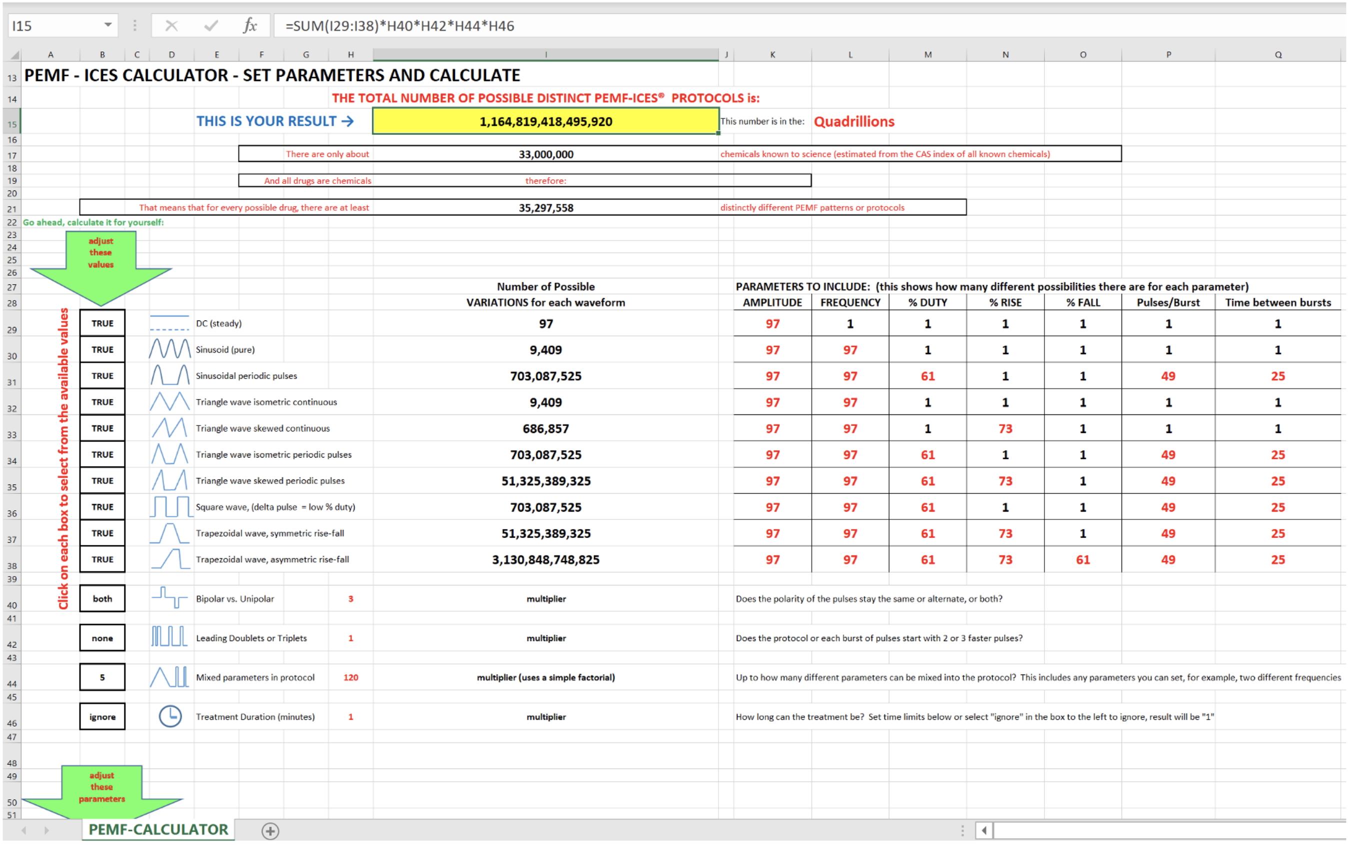

Figure 1. *Screen shot of the PEMF Calculator spread sheet with default values*

The number of possible variations of PEMF is easily adjusted for any reasonable types and ranges of parameters. For example, to limit possible forms of PEMF, DC magnets (DC steady) can be set to FALSE, set Leading Doublets or Triplets to “none” and reduce the number of mixed parameters (waveform shapes) to 1. Include treatment time as a parameter, then reset the amplitude and frequency ranges to those more commonly used in consumer PEMF systems. Adjust the tolerance of each to “20%” to reflect the fact that smaller changes in frequency and amplitude have not been shown reliably in any scientific publication to yield measurably different biological responses. Then, reduce the number and time between bursts to 1 (maximum and minimum) so that only continuous PEMF pulsing is considered. Finally, set the range of treatment times from 1 to 100 minutes, which is approximately the maximum range generally considered clinically practical. With all of these changes, the resulting calculation becomes:

10,003,393,125 possible variations of PEMF

This is a much smaller number than the default calculation of ~ 1 Quadrillion, but still some 300 times larger than all known chemical species in the universe.

It is possible to narrow this further. Recalculating for a very restrictive set of parameters, considering only unipolar square waves, excluding all other waveforms, and setting the amplitude and frequency to a narrow range commonly used in commercial PEMF (0.1 to 1000 Gauss, 1 Hz to 1000 Hz), and neglecting treatment time as a parameter, the result is still 57,950 possible variations of PEMF.

By resetting parameters to reflect the PEMF parameters under consideration, it is possible to determine the number of variations available for any subset of PEMF parameters, such as excluding only sine waves, which are widely believed to be ineffective for therapeutic PEMF, limiting the frequency or amplitude to a narrowly specified range, or restricting consideration to only one type of waveform, such as trapezoidal, for example. For regulatory-related estimates, the number of variations can be calculated for a specified range of dosages related to PEMF treatment time and pulse amplitude.

This spreadsheet is available for download and experimental use at this link:
http://downloads.corticalmetrics.com/JoSaM/PEMF-Calculator.xlsx

The use of this spreadsheet requires Microsoft Excel, Office 2013 or later. The author accepts no responsibility for liability or loss as a result of the use of this spread sheet. Such use is expressly intended for educational purposes only.

Discussion

By any calculation, the number of possible variations on PEMF are enormous. Clearly, it makes no sense to ask the question “Does PEMF work?”, because PEMF can mean so many different things, and in its various forms PEMF has been reported to have so many different biological benefits.

Because there is no accepted standard for the detailed parameters of therapeutic PEMF, and the parameters themselves are not universally agreed upon, it is likely that others might take a different view on exactly how such a calculation should be made. In this model, we simply attempted to define the terms of the question carefully, apply numbers to those terms, set the ranges and tolerances, tally up all possible combinations of parameters, and sum them together to yield a total number. Whether this sum represents truly different “forms” of PEMF, or if some of these are just minor variations, and whether the differences reflect changes in real biological responses or just arbitrary regulatory definitions, these are all matters for continued discussion. The objective of this model was simply to demonstrate the scope and magnitude of PEMF, based on how precisely the terms of the question are defined and quantified.

By inserting different ranges, tolerances, and by excluding or including different variations on PEMF, a total number of possible variations has been calculated. This result can be used to inform design, experimental, or regulatory considerations and decisions.

These results do suggest that a serious re-thinking of the way PEMF is regulated is in order, because it is simply not mathematically possible or clinically useful to attempt to make certain distinctions, while other distinctions that may seem minor are crucial to the efficacy (or not) of PEMF. For example, all other things being equal, a difference of pulse frequency of 1% is not likely to result in different biological effects, but the change in waveform shape, from sine to square for example, even at precisely the same frequency, would constitute completely different electromagnetic phenomena, and would rightly be viewed as entirely different forms of PEMF [3].

These results can also give guidance as to how to formulate experiments to test different variations on PEMF. It was precisely this approach that guided the development of the first set of NASA-JSC TVEMF experiments [2], where the primary objective of the experiment was to determine which waveform shapes might be most effective, holding all other parameters constant (pulse frequency, pulse polarity, pulse duration, and peak magnetic field amplitude) [3]. This reduced the number of PEMF variations that could be tested from about a quadrillion to a much more manageable quantity: six. In that earlier work, it was found that only square and delta waves yielded repeatably detectable biological effects, the other four waveform shapes were ineffective. In subsequent work [6] it was demonstrated that the pulse frequency was not critical, but the pulse shape and the total number of pulses applied determined the effective dose and the resulting biological effect.

Another result is somewhat sobering. It becomes clear that the simple question “does PEMF work” is absolutely unanswerable as stated. The scope of PEMF is so vast that, as shown at the top of the calculator results Figure 1, that the number of different variations of PEMF greatly exceeds the total number of chemical species in the known universe. This total number will vary depending on the inputs to the model, but using the default values, the number of possible variations of PEMF would be about 35 million times greater than the total number of known chemicals. So, asking whether “PEMF works” would be as fruitless as asking whether “chemicals work”, without specifying exactly which chemical. Just as it is essential to define a chemical before testing it and drawing any conclusions, it is equally important to carefully define PEMF before using it in an experiment, or drawing any conclusions about whether or not it has any detectable biological effects. This simple fact seems to have been overlooked in the majority of publications in the field of PEMF.

Upon comprehensive review of all available papers in the entire field of PEMF as of the year 2000, in all languages, the author determined that only about 3% contained sufficient information to define most of the PEMF parameters necessary for a clear definition of the form of PEMF being used. More recent published work may have improved somewhat in this regard, but not uniformly.

An attempt was made to include a calculation for all well-defined variations of PEMF. It should be noted that there are many poorly-defined PEMF waveforms on the commercial market at the time of this writing. This includes PEMF that is based on pulses or waveforms that intentionally or unintentionally have random parameters, are dominated by electro magnetic noise, or those based on crude pulse transmitters, such as the recently popular “spark gap technology(!)” PEMF systems. It should be noted that spark gap generators [8] are considered obsolete precisely because they are highly variable and generate non-defined waveform pulse shapes characterized by excessive amounts of electromagnetic noise. Radio transmission of the spark-gap type has been prohibited by international law since 1934, but spark gaps remained in common use for several more decades as crude electronic timing and oscillating mechanisms, until largely overtaken by vacuum tubes, then transistors. It would be impossible to calculate the number of different variations possible with PEMF using such crude instruments, because they vary so unpredictably, from pulse-to-pulse.

Conclusions

Using reasonable initial ranges for PEMF parameters, there are more than 1 quadrillion different variations of PEMF that could be applied, tested, or regulated. One “quadrillion” is a real number, unlike “gazillion” or “brazillion”, and it represents one possible calculation of the total number of different variations on PEMF, and it is very large indeed. By understanding the size and source of this enormous number, and by clearly defining the terminology involved with its calculation, then using these to formulate precise questions, the study of the biological effects of PEMF becomes much more tractable. It will also open the gateway to understanding the biophysical mechanisms of PEMF on living systems. The study and regulation of PEMF will be improved greatly by understanding the scope and magnitude of the number of possible variations of PEMF when the parameters are clearly defined.

Statement of Potential Conflict of Interest

The author of this report (R.G. Dennis) declares both a scientific and a commercial interest in ICES®-PEMF technology: He is owner of Micro-Pulse LLC (manufacturer of the technology), holds several patents for ICES®-PEMF technology and receives royalty payments from NASA-Johnson Space Center for the commercial licensing of this technology, which he developed in its initial form (TVEMF) as a consultant for NASA in the mid-1990’s.

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