Sonoluminescence: Making Light of an Unclear Past and Exploring the Path Forward

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Parker Thomas George

Abstract

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Sonoluminescence is an acoustic phenomenon in which a bubble can be driven acoustically to collapse an emit a rapid burst of light. While this phenomenon was initially discovered in the 1930s, research in the field did not peak until 1989 when stable, single bubble sonoluminescence was observed and reported. The author will present an introduction and overview of this phenomenon, and then will provide a brief history of the key research findings in the field between the initial discovery and the present. In particular, the claim that "sonofusion" could be achieved will be addressed and unpacked. An argument will then be put forth that sonoluminescence was unfairly associated with this "sonofusion," and that this led to a decline in research in the field, particularly in the applied space. In response, the author will introduce a novel approach to using sonoluminescence as a medical screening tool, along with a suggestion for how such an apparatus could be constructed.

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Chapter 4

Credibility of Sonofusion

Taleyarkhan's unwavering support of his 2002, 2004, and 2006 papers in the face of their near complete rejection by the academic community warrants an interesting discussion about the standard by which science judges whether or not a result is "correct." By the end of 2006, only Suslick, Shapira-Saltmarsh, Putterman, Xu-Butt, Forringer, and Bugg had put forth attempts to replicate the Taleyarkhan experiment and achieve consistent fusion results, as Taleyarkhan had. However, as shown in Chapter 3, the Suslick, Shapira-Saltmarsh, and Putterman experiments each had certain design differences compared to Taleyarkhan's setup in such a way that one could argue prevent each experiment from completely refuting the results reported by Taleyarkhan's apparatus. On the other hand, the researchers that had published or announced confirmatory results–Xu-Butt, Forringer, and Bugg – all had some degree of interaction with Taleyarkhan's lab or expertise, which equally raises questions about the validity and independence of these confirmations.[1]

With only 6 attempts having been made to replicate Taleyarkhan's fusion results, and with each of these attempts having some detail that may negate them from representing a perfect replication attempt, is this enough to rule that Taleyarkhan's reports of fusion were

[1]Appendix A provides further detail about the Xu-Butt publications and Taleyarkhan's connection to them

incorrect? If not, then how much more evidence should be required before this claim can be made? The goal here is not to comment on the quality or validity of any of these specific attempts, but rather to press the issue of how, why, and when the academic community accepts something as fact, and to challenge whether or not this standard was fairly applied to Taleyarkhan and his fusion claims.

Two, arguably competing factors are in play here. The first is the question of what makes a claim factual. The second, more particular to the potentially world-changing claim of fusion production, is the idea that extraordinary claims require extraordinary evidence. The former seeks to address what kind of evidence, and how much of it, is needed to empirically prove something as correct. The later seeks to condition this based upon the significance of the claim made.

Regarding the first factor, at the surface level, facts should be binary. $1 = 1$ is either "True" or "False" – a fact or not a fact. In traditional math, there will never be a scenario where the outcome of this unknown or uncertain. This can be proven mathematically, and just as well can be proven observationally. "There is one ball on this table and one ball on that table; are the number of balls on each table equal?" When the answer to this question is yes, the statement that $1 = 1$ can be proven true.

Likewise, Taleyarkhan's claim of fusion should give rise to a similarly binary result. Either fusion did occur, or it did not. The problem, though, is that Taleyarkhan's fusion observations are not observable in the way that the claim of $1 = 1$ can be. Suslick, Shapira-Saltmarsh, and Putterman all constructed their own apparatuses, and in doing so introduced a degree of variability in the system. Similarly, Xu-Butt, Forringer, and Bugg, though Taleyarkhan's equipment may have been used, nonetheless conducted their own experiments, which also added that degree of variability and subjectivity. As a consequence of this, inference and speculation play a role in how each experiment is used to comment on the factual nature of Taleyarkhan's claims. Specifically, inference and speculation must be used to bridge the gap between the findings of each replication attempt and the claims of Taleyarkan's. Were each experiment to have been a perfect replication with Taleyarkhan's help (but not direction), perhaps the results of such experiment could be treated in a similar way to the "balls on the table" scenario mentioned above. Instead, each group of scientists is forced to draw a conclusion that "the findings of my experiments *mean* that the findings of Taleyarkhan's experiments were incorrect."

This is now no longer a binary situation. A good replication attempt should lead to a higher degree of confidence in this inference, and a worse replication attempt should lead to a lower one. Given though that what separates a "good" replication from a "bad" one can be difficult to quantify and qualify, this could possibly mitigated statistically with the law of large numbers. Given a large enough sample size, the variability of replication quality should average out, and a large enough sample size should asymptotically approach the true result of the original claim. If 100 or 1000 attempts are made to replicate, provided these are all based on some sort of evidence or experimental grounding, then perhaps this would be "enough" evidence that the inferences made from these experiments, on average, are indicative of the true result of the original experiment's claim. This would solve the issue created by inference and supposition because it returns the conclusion back to a decently binary one.

Unfortunately, the answer to the question of how large this sample needs to be is not as simple as the classical suggestion that $n = 30$ is "enough." Instead, this heavily depends the type of claim or result being made. Just as the clinical trial process for the release of a new medical drug is long and multi-faceted, claims that have much at stake necessarily need a higher degree of certainty than others, and this higher degree of certainty requires either a large number of confident, successful tests or the assurance that the tests which do report successful outcomes are robust and well enough designed to be satisfactory replications. This brings into play the second of the two factors at stake here.

The late astronomer Carl Sagan made famous the aphorism that "extraordinary claims require extraordinary evidence." Such a quote can even be traced back to David Hume.[58]. Regardless of the original source, the implication is simple. Claims that are particularly extraordinary in nature demand extraordinary evidence. As explained in the opening of Chapter 3, Taleyarkhan's claims of fusion from sonoluminescence certainly meet the criteria for "extraordinary." If true, they could revolutionize energy production while simultaneously undermining other efforts at clean energy.

So Taleyarkhan's fusion claims certainly require extraordinary evidence, but what qualifies as extraordinary evidence? The law of large numbers, referenced above, suggests that extraordinary evidence could could come in the form of an extraordinary quantity of evidence. But how much, then? Rather neatly, Bayes' theorem may provide an answer, or at least a framework in which to consider postulate an answer. As depicted in 4.1, Bayes' theorem is a method of calculating conditional probabilities – the probabilities of one thing conditioned by the probability another. Using this, we can begin to calculate the likelihood that an extraordinary claim is true, given how extraordinary the evidence is in favor of such a claim.

$$P(A \mid B) = \frac{P(B \mid A)\, P(A)}{P(B)} \tag{4.1}$$

As an example, consider the claim that someone could guess which number a six-sided die would produce nearly every time it were thrown. Provided the die is weighted evenly, the near perfect ability to guess this would almost certainly be extraordinary. But just how much evidence would we need in order to feel comfortable accepting this seemingly psychic claim? Bayes' theorem can roughly provide an answer. If we interpret "nearly every time" to mean 95% of the time, assume that the true probability of our friend being psychic is about one-in-a-billion, and know that the probability of a die landing on any of its six sides is one in six, or ˜ .167, then we can fill out Bayes' theorem as is done in 4.2, and conclude that the likelihood that our friend is psychic, given only one throw of the die, is extremely low

– just about 5 in-a-billion. Re-contextualizing, this calculation indicates that the evidence, $P(B)$ is just not extraordinary enough to confidently substantiate a claim.

$$5.69 \times 10^{-9} = \frac{.95 * 1 \times 10^{-9}}{\frac{1}{6}} \tag{4.2}$$

At 10 correct guesses, though, the likelihood of our friend guessing soars to .054, or a little more than one-in-twenty. At 11 guesses, this jumps again to .33, now almost one-in-three. Perhaps now we may be comfortable believing our friend is not guessing after all. More specifically, maybe 11 correct guesses is extraordinary evidence.[2] Even though the likelihood our friend is a psychic is just one-in-a-billion, the presence of this evidence now makes this likelihood much higher. This is Bayes' theorem in action.

This same logic can be applied to claims about fusion. Assigning descriptions to each variable, $P(A \mid B)$ would represent the likelihood that Taleyarkhan's claim of observing fusion is correct given the totality of the evidence presented. $P(B \mid A)$ would represent the likelihood of the evidence presented given that Taleyarkhan's claim were true. $P(A)$ would then represent the likelihood that Taleyarkhan's claim was truthful, and $P(B)$ would lastly represent the likelihood of the evidence in favor of the claim.

Assigning descriptions to each variable, $P(A \mid B)$ would represent the likelihood that Taleyarkhan observed fusion given the evidence presented. $P(B \mid A)$ would represent the likelihood that evidence of fusion would exist if Taleyarkhan did observe fusion. $P(A)$ would represent the probability that Taleyarkhan observed fusion, and $P(B)$ would represent the likelihood that evidence of fusion would exist.

Unfortunately, the probability of each of these items is much less intuitive than the example of our psychic friend. $P(B \mid A)$ seeks to address the likelihood of a replication

[2]In this particular example, calculating $P(B)$ from 12 rolls of the die produces a probability that is greater than 1. This is merely a result of the assumptions made about the denominator, $P(B)$. According to the Law of Total Probability, $P(B \mid A)\,P(A)$ should never be greater than $P(B)$, since $P(B) = P(B \mid A)\,P(A) + P(B \mid \neg A)\,P(\neg A)$.

attempt succeeding if it were certain that Taleyarkhan had observed fusion. While this should, in theory, be 100%, Taleyarkhan himself would likely disagree. Even if Taleyarkhan had achieved fusion, it may be possible that another experiment seeking to replicate these results would not be able to. If we are to accept this as a possibility, then $P(B \mid A)$ cannot be 100%. Erring on the on the safe side, perhaps this would occur approximately one-in-ten times. Therefore, $P(B \mid A) = .9$. Moving on, $P(A)$ needs to reflect the extra-ordinariness of Taleyarkhan's fusion claim. We know from the extreme conditions required that the claim of fusion is already unlikely, and the claim that fusion could be achieved in a table-top apparatus, rather than a large-scale fusion reactor like the ITER even further decreases these odds. If we loosely assume that the probability of successful net energy positive fusion from the ITER is about one-in-1,000, and that the ITER apparatus is about 100,000 times more likely to produce fusion than a table-top one, then we arrive at a highly approximated, but conveniently simple, probability of $P(A) = \frac{1}{1{,}000{,}000}$.

That leaves $P(B)$ to be accounted for. From the Law of Total Probability, $P(B)$ can be expanded to

$$P(B) = P(B \mid A)\,P(A) + P(B \mid \neg A)\,P(\neg A)$$

We know from above that $P(B \mid A)\,P(A) = .9 \times \frac{1}{1{,}000{,}000}$, and that $P(\neg A) = 1 - P(A) = \frac{999{,}999}{1{,}000{,}000}$, so what remains to be assigned a value is $P(B \mid \neg A)$, or the liklihood that the evidence exists given that Taleyarkhan's claim was false. In a perfect scientific world, we would hope that this value would be zero. If an original claim is incorrect, then no replication attempt should be able to produce a confirmatory result. Unfortunately, false-positives do exist, and the more speculation and inference that goes into a result, the more likely a false-positive will be. With that, could it be possible to a replication attempt to report positive findings even if Taleyarkhan truly did not? If so, how likely? This answer to this becomes the variable that dictates the extraordinary nature of the evidence.

n \ p	1	2	3	4	5	6	7	8	9	10
0.3	0.0000	0.0000	0.0000	0.0001	0.0004	0.0012	0.0041	0.0135	0.0437	0.1323
0.2	0.0000	0.0000	0.0001	0.0006	0.0028	0.0139	0.0657	0.2601	0.6374	0.8978
0.1	0.0000	0.0001	0.0009	0.0089	0.0826	0.4737	**0.9000**	**0.9890**	**0.9989**	**0.9999**
0.01	0.0001	0.0089	0.4737	**0.9890**	**0.9999**	**1.0000**	1.0000	1.0000	1.0000	1.0000
0.001	0.0009	0.4737	**0.9989**	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.0001	0.0089	**0.9890**	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 4.1: $P(A \mid B)$, for n-number of positive, independent replications each with p-likelihood of being a false positive.

Rather than speculate on what this particular value should be, a sensitivity analysis can be used to calculate how various combinations of this probability and the number of replication attempts affect the calculation of $P(A \mid B)$. Table 4.1 demonstrates this. On the y-axis are various levels of $P(B \mid \neg A)$ for an individual positive replication, and on the x-axis are the number of positive replications.[3] Operating on the assumption that each positive replication occurs independently from one another, the cumulative value of $P(B \mid \neg A)$, where all the positive replication attempts are false-positives, would be the individual probability raised to the power of the number of replication attempts.This probability would then be multiplied by $P(\neg A)$ and then added to $P(B \mid A)\,P(A)$ to arrive at $P(B)$.

The stair-stepping border in Table 4.1 indicates values where $P(A \mid B)$, the likelihood that Taleyarkhan's claim is correct given the evidence presented, is greater than or equal to a 90% confidence level.

Two key observations can be made from this chart. The first is the exponential effect that the probability of a false-positive plays on the calculation of confident $P(A \mid B)$ value. For five positive, independent replication attempts, decreasing the probability of a false-positive from $p = .2$ to $p = .1$, only a 50% decrease, gives rise to an increase in the difference between a false-positive probability of .2 and .1 is an increase of $P(A \mid B)$ by nearly a factor of 30, from .0028 to .0826.

[3]The term "positive replication" is used here to define a replication that produces (positive) evidence in support of Taleyarkhan's claim.

The second is that, in spite of what traditional statistical intuition may say about significant sample sizes, at even a very high probability of a false-positive ($p = .3$), just over 10 positive, independent replication attempts would be required to overcome the extraordinariness of Taleyarkhan's claim of fusion – not 1000, 100, or even 30, as one may be led to expect. For very low values of the probability of a false positive ($p \leq .01$), only a few positive, independent replications would be needed to overcome the burden of proof created by the high unlikelihood of Taleyarkhan's claim.

Given the discussion earlier about the subjectivity introduced by the inference and supposition required in each replication, there would certainly seem to be a possibility of a false-positive replication, even if Taleyarkhan did not actually achieve fusion. However, liberally assuming that the probability that each positive replication could the result of a false positive falls in the range of $.01 \geq p \leq .2$, then at worst, only 11 positive, independent replications would be needed, and at best, just four.

So what insight does all of this statistical discussion provide into Taleyarkhan's claim of sonofusion and the evidence surrounds it. Put succinctly, given the evidence that exists currently, Taleyarkhan's claim does not fall above the line in Table 4.1. With respect to Sagan's statement, the evidence that exists in support of Taleyharkhan's claim of sonofusion is insufficient to justify such a claim. There's just not enough proof.

But why not? Perhaps Taleyarkhan's claim truly was false and he never actually observed evidence of fusion from sonoluminescence. And to be certain, the evidence that exists in the form of independent replications that could not produce positive, replicative results (Suslick, Shapira-Saltmarsh, and Putterman) increases the amount of evidence required above what is suggested in Table 4.1. But in spite of all of this, only seven replication attempts have been made *in total*. Taleyarkhan touts the simplicity of his experimental setup, and even Putterman was reported as having once used his own money to purchase the equipment necessary to build a sonoluminescence apparatus.[51]. In the best possible outcomes for

Taleyarkhan, some of these attempts may produce positive sonofusion results and some credibility may be added to the claim. But at worst, negative results would only further lay to rest the idea that sonofusion was impossible, and hopefully allow sonoluminescence research to move on.

Instead, the lack of popularity that any sonoluminescence-related publications have received since the Taleyarkhan fusion papers suggests that the research, especially in the applied field, has been stunted by the controversy surrounding sonofusion and the failure to properly lay the claim to rest.

While this may feel draconian, the reception of Taleyarkhan's publications significantly affected the popularity of sonoluminescence and sonoluminescence research as a whole in an extremely negative way. With the Gaitan single-bubble publication in 1990, sonoluminescence began to experience a Golden Age of research. As mentioned in the 2 chapter, scores of papers were published, a movie was released, and the British Broadcasting Corporation even funded the Seth Putterman lab to conduct sonoluminescence research. Taleyarkhan's fusion results, though, marked the end of this Golden Age.

To understand why, consider an engineer or physicist in 2006 looking to explore and begin an innovative new project. At this point in time, sonoluminesence would now be the last place he or she would want to look. As a direct result of Taleyarkhan's work and the news and media coverage that surrounded it, sonoluminescence and "sonofusion" have become all too easily synonymous. This would undoubtedly lead issues if and when one needed to seek funding. At the university level or national lab level, why would any research institution wish to associate itself with what had been publicly received with so much controversy? At the funding allocation level, why would any source of funding wish to allocate its resources to something which has received so much attention yet produced so little to show for? These claims are intentionally over-dramatized, but with the competitiveness of scientific grant funding, it should become how easily claims like these manifest.

This inevitably led to a decline in sonoluminescence research and publications, especially in the applied space. A cursory search through the first 10 results pages on Google Scholar for "Sonoluminescence Application" and "Applications of sonoluminescence" reveal a startlingly low number of relevant results that directly involve sonoluminescence. Though "about 4,450" results are returned, the overwhelming majority of these publications pertain to cavitation and sonochemistry, and simply note sonoluminescence as an observed and occasionally measured side effect. Very, very few papers involve sonoluminescence as the primary subject matter.

One search result was a paper titled "A Practical Application of Sonoluminescence to the Evaluation of The Cavitation Potential of the Mechanical Heart Valve," which suggested that sonoluminescence light production could be measured as a proxy for the presence of potentially damaging cavitation in artificial heart values.[59] Another, titled, "Multi-bubble Sonoluminescence: Laboratory curiosity, or real world application?" posited the novel idea of using sonoluminescence to activate photosensitizing drugs used to treat cancer cells.[60][4] It also suggests that sonoluminescence may have a purpose in destroying contaminants during the manufacturing process of semi-conductors, a claim that is further corroborated by a 2011 paper from the Japanese Journal of Applied Physics.[61].

In spite of how potentially viable these possible applications (and the few others not mentioned above) may be, no paper has received near the media or scientific attention that any of the Taleyarkhan papers received. Whereas Taleyarkhan's 2002, 2004, and 2006 papers have been cited (according to Google Scholar) 555, 186, and 146 times, respectively, both of the above papers have been referenced just once, each. Much of this can be attributed to the differences in popularity between the journals in which these findings were published. However, at least some has to be the result of the fact that scientists in the field have shied

[4] It interesting to note the timidity that comes across in this title. Despite the sound overview of Sonoluminescence that the article offers, "Laboratory curiosity" reads as if the authors were attempting to hedge against the claim of sonoluminescence's uselessness

away from sonoluminescence as a direct result of Taleyarkahn's fusion research and the way the academic community responded to it.

Chapter 5

The Path Forward

With interest and publications surrounding sonoluminescence having declined in the years following 2006 and the Taleyarkhan findings, an empty space was created in the field. While much progress has been made in the way of identifying and attempting to understand the underlying mechanisms of the phenomenon, there has yet to be another, ground-breaking and news-worthy discovery or publication regarding sonoluminescence. Such a discovery, however, might already have been made and simply needs to be brought to light.

Initially published in 1989 in the Journal of Soviet Physics Acoustics, a Russian (then Soviet Union) scientist at the Russian Institute of Applied Physics by the name of Vladimir Chernov presented findings that suggested sonoluminescence could be used as a blood-based medical diagnostic and screening tool. In the paper, titled "Ultrasonic luminescence of blood plasma and the diagnosis of cancer," Chernov and co-authors S.M. Gorskii, I.D. Karev, I.G. Terent'ev conducted "422 luminescence measurements...on blood plasma from donors, from patients with various chronic illnesses, and from patients with primary cancer localizations (in the stomachs, in the lungs, etc). [62] The sonoluminesence intensity measurements over time are reproduced in Figure 5.1. Reportedly, a clear difference exists between line a, blood donors (negative control); line b, "patients with chronic diseases of nonmalignant genesis";

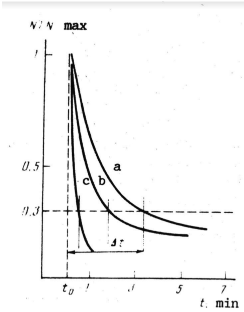


FIG. 1. Normalized luminescence intensity vs time at a constant ultrasonic excitation amplitude for blood plasma from: a) Blood donors; b) patients with chronic diseases of nonmalignant genesis; c) cancer patients.

Figure 5.1: From Chernov et al., Normalized Sonoluminescence Intensity over time for three types of patients.[62]

and line c, patients with cancer.[62]

Chernov et. al further supported this finding with another publication in 2003, published this time in Volule 6 of the Hydroacoustics Annual Journal. This article, "Sonoluminescence of water and biological fluids" tells a smiliar story. This time, 465 patients were tested, where 395 (84.9 %) were considered pathological and 70 were healthy.[63]. Figure 5.2 depicts Chernov's results for one set of patients.[63] The top three curves represent normal blood plasma patients (control) the second from the bottom is from a patient with "cancer blood plasma;" the bottom is a patient with AIDS. This result is particular intriguing, for each of the three sets of curves differs significantly from one another. This significant difference is made even more apparent in Figure 5.3, which plots the sonoluminescence Index, K, which normalizes outputs against a negative control of distilled water.[63] Though the lower bound of the error bar is not discernible, assuming the lower tail matches the upper, the sonoluminescence Index of each disease group appears to be significantly different from one another.

From a combination of the two papers, it can best be deduced that Chernov's measurement process resembled something of the following:

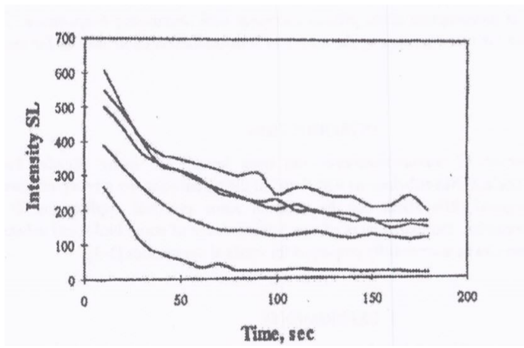


Figure 5.2: Dependency of sonoluminescence intensity over time for five different patients. The Y-axis represents sonoluminescence intensity by way of photon count, and the X-axis represents time.[63]

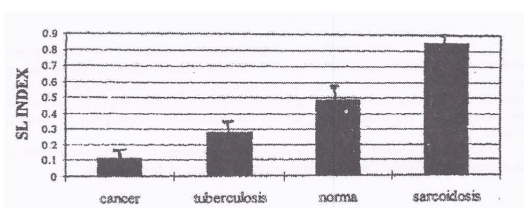


Figure 5.3: Distribution of the sonoluminescence index across different diseases and control (normal) group.[63]

1. Draw blood from patients
2. Isolate blood plasma from blood sample
3. Leave blood plasma in contact with air for at least 1, 24 hour day
4. Expose blood plasma sample to driving frequencies of 350 kHz, 530 kHz, and 780 kHz at a power no greater than 10 W
5. Measure sonoluminescence intensity (number of photons) every 10 seconds (averaging period) in the 300 nm to 700 nm range emitted from the sample over time
6. Compare the Intensity/time plot against known samples

In short, these two papers indicate sonoluminescence could be effectively used to screen for, and even potentially diagnose a number of communicable diseases and cancers. As will be explored later in Chapter 6, the implications of such a device would be revolutionary. Shockingly, though, nothing came out of these two papers. None of the leading sonoluminescence researchers mention either paper in recent publications, and Google Scholar indicates that the 2003 paper has only been cited one time, in specific by a paper published in Russian.

Even more interestingly, Vladimir Chernov appears to have published no other papers involving sonoluminescence past 2003, and no papers at all past 2008.[64] [1] Additionally, in an effort to seek further information about these findings and the experimental setups used, the author of this thesis has made multiple unsuccessful attempts to contact him. This was done both through the email address listed on his publications and through his email addresses co-authors and contributors on other papers. These emails were sent both in English and in Russian, but neither language has elicited a response from any of the

[1] The Kuehne Physics Mathematics Astronomy Library at The University of Texas at Austin contains a complete collection of Soviet Physics Acoustics journals from 1970 to 1989. In the entire 20 year collection, Chernov's name only appears three times. Once in 1980 in a paper titled "Singular features of the ultrasonic fluorescence spectrum of water", once in 1985 in a paper titled "Influence of oxygen on the intensity and spectrum of the ultrasonic fluorescence of water," and once in the paper cited above.

contacted authors. Attempts were even made to locate Chernov through contact information provided by the Russian Institute of Applied Physics and the Russian Academy of Sciences. These too have been unsuccessful. Chernov, as of the writing of this thesis, seems to no longer exist.

However, while neither Chernov nor any other scientist appears to have made an attempt to replicate his 1989 and 2003 findings, a variety of other publications have since come along that offer strong indirect support of the validity of sonoluminescence as a blood-based screening and diagnostic tool.

Most notably was the 2016 publication of a paper entitled *Diagnosis and Classification of 17 Diseases from 1404 Subjects via Pattern Analysis of Exhaled Molecules* published in the ASC Nano journal. [65]. In particular, Nakhleh et al. "report on an artificially intelligent nanoarray based on molecularly modified gold nanoparticles and a random network of single-walled carbon nanotubes for noninvasive diagnosis and classification of a number of diseases from exhaled breath." [65] Specifically, Nakhleh et al. built a quasi- "breathalyzer," which could, with a high degree of accuracy, diagnose and classify one of seventeen different diseases that the patient may have had.

Though the authors of the paper report that the"breathalyzer" is being researched and make no indication of when it may commercialized or made available to medical institutions, the implications of such a device are massive. Human breath is readily available in all patients and can be obtained almost effortlessly and with little to no risk of concern of spreading contagious or communicable diseases. Equally importantly, such a device also significantly reduces the financial and educational barriers to entry associated with the other methods of screening for and diagnosing these diseases. Of the seventeen different diseases explored in the paper, eight were types of cancers, which would traditionally require radiology tests, endoscopy procedures, and/or biopsy tests.[66] To a patient without insurance, endoscopy tests can easily costs thousands of dollars. Biopsies and radiology tests, while cheaper, are also still cost-prohibitive to many. Likewise, each of these tests involves a combination of trained nurses, doctors, and lab technicians. As a result, the opportunity for a device that could reduce either of these costs is massive. And, owing to the massive publicity that this article has received, the public seems to be equally understanding of this significance. These costs will be further explored in Chapter 6.

Returning to the publication, Nakhleh et al.'s apparatus differentiated between each disease through measurable differences in volume of a variety of different volatile organic compounds. According to the American Lung Association, Volatile Organic Compounds, or VOCs, are highly evaporative gasses emitted from certain solids or liquids, which may have short term and long term adverse health affects.[67]. Many commercial and industrial processes emit these gasses, which are then absorbed into the body when one interacts with and breathes the air into which they have evaporated. [2]

Summarizing the Nakhleh paper heavily, a pattern of volumes and concentrations of VOCs were discerned for each of the 17 diseases, and then the breath sample entered into the apparatus would then be algorithmically compared to this pattern, and the pattern with which the sample matched most closely would be returned as a possible match and diagnosis. Put more simply, minute differences in chemical concentrations of the breath sample could be used to, with a high degree of accuracy, diagnose a patient with one of 17 different diseases.

Thus, just as Nakhleh found with breath, minute differences in chemical concentrations of a blood sample could, reportedly, be used to screen for or diagnose a variety of different diseases. Excitingly, though, the connections between these two reports did not simply end with the processes or the results.

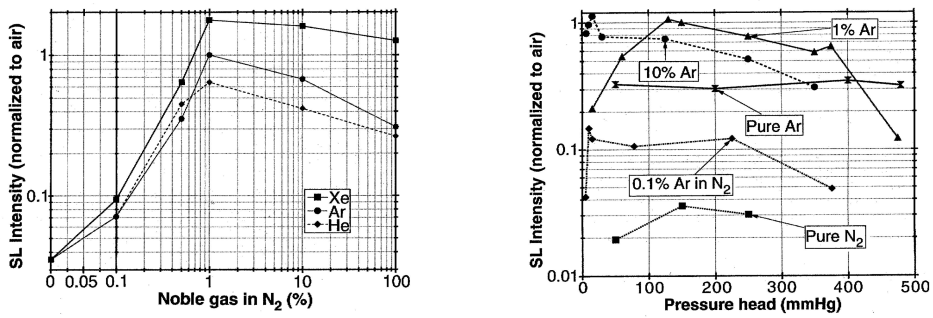
[2]For a complete list of Volatile Organic Compounds and their specific health effects, see the Agency for Toxic Substances and Disease Registry Toxic Substances Portal, found here: `https://www.atsdr.cdc.gov/substances/index.asp`

Regarding the connection between these two experiments, the first is that of VOCs in breath and blood. Literature exists that connects the the presence and concentration of VOCs in breath with VOCs in blood. Mochalski et al. and O'Hara et al. both posit that a correlation exists between the concentration of VOCs in blood and the concentration of VOCs in breath. The Mochalski study notes that 12 of the 74 compounds (16.2%) were "simultaneously present in both fluids ($>$ 90% occurrence)." [68]. However, O'Hara et al. does express replication concerns with respect to the measurement of VOCs in blood, noting that the "coefficients of repeatability as a percentage of mean are less than 30% in breath but greater than 70% in blood."[69].

While 12 out of 74 is admittedly lower than desired, the point of drawing connection is not to demonstrate how similar the VOC concentrations are between blood and breath. Instead, the fact that this number is non-zero should be received as positive evidence that there is *some* connection the chemical composition of breath and the chemical composition of blood.

Second, abundant research exists detailing the effect of dissolved gasses on sonoluminescence intensity and spectral output. This effect was observed and published in 1994 by Hiller et al., specifically about the effect of noble gasses on sonoluminescence. In specific, Hiller et al. note, "increasing the noble gas content of a nitrogen bubble to about 1% dramatically stabilizes the bubble motion and increases the light emission by over an order of magnitude to a value that exceeds the sonoliminescence of either gas alone." [70] Figure 5.4 demonstrates a clear difference in normalized Sonoluminescence light intensity with respect to concentration of argon relative to nitrogen, and also a clear difference in how different pressures at which the noble gas was dissolved into the bubble affect Sonoluminescence intensity for different dissolved concentrations of dissolved argon.

This effect of gaseous content on sonoluminescence intensity was further explored by a a 2016 paper published in Ultrasonics Sonochemistry entitled *Influence of dissolved gases*



(a) SL intensity vs. gas concentration[70]

(b) SL intensity vs pressure[70]

Figure 5.4: From Hiller et al, effect of concentration (left) and pressure (right) on SL Intensity.[70]

on sonochemistry and sonoluminescence in a flow reactor.[71]. Here, the effect of dissolved argon, air, nitrogen, and carbon dioxide Sonoluminescence yield was examined in terms of the number of photons observed over a 30 second period using a a photon counting head.

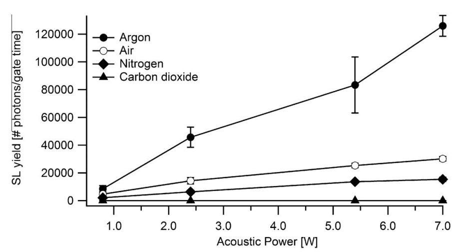


Figure 5.5: From Gielen et al., Sonoluminescence yield, displayed as the number of photons per gate time, as a function of the acoustic power for different gases at a frequency of 248 kHz.[71]

Graphical representation of these differences Figure 5.5 and Figure 5.6, reproduced from Gielen et al., show the results of this experiment at frequencies of 248 kHz and 47 kHz, respectively.[3]. With the exception of measurements at .8 W, all measurements of photon counts were significantly different from each other. As with the link between chemical

[3]As noted by Gielen et al. At all power levels at both frequencies, solid lines shown connecting measurement points were added to aid in the detection of a trend and do not represent any measurement or model

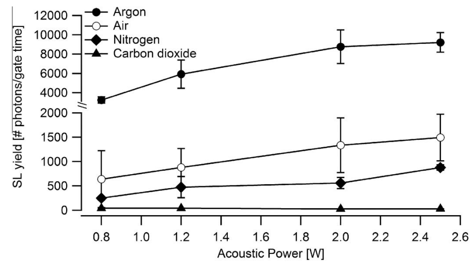


Figure 5.6: From Gielen e. al., Sonoluminescence yield, displayed as amount of photons per gate time, as a function of the acoustic power for different gases at a frequency of 47 kHz.[71]

compound concentrations in blood and breath, it is again important to note the observed differences in output in Figures 5.5 and 5.6 are not an attempt to provide a causative explanation of the differences in sonoluminescence output from the Chernov experiment. Rather, these figures, and the Gielen study as a whole, is included merely to show that literature exists that confirms the dependency of sonoluminescence output on dissolved gasses, but not necessarily any gasses in particular.

In summary, then, it is known from existing, peer-reviewed literature that:

- Chemical composition in breath can be used to screen for and diagnose different diseases
- A connection exists between chemicals in breath and chemicals in blood
- Sonoluminescence output is heavily dependent upon the type and concentration of dissolved gasses in the fluid medium

Thus, despite the limited information that the Chernov papers provide, and the lack of any documented attempts to replicate the experiments, the literature peripheral to blood as a screening and diagnostic tool affords a degree of viability to Chernov's findings. And, even if the possibility of this viability is quite small, the implications of a successful device, as will be seen in the next chapter, easily warrant and demand further investigation into Chernov's work.