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Scientific Replicability: Two Cases of Study in Laser Physics

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Abstract

One of the most important characteristics of modern science is its replicability and objectivity. This means that a scientific result is taken as such only when it has been reproduced by other scientists. Indeed, the replicability of a scientific result in an objective and independent way by members of a scientific community is the cornerstone of science. Experimental laser physics is an example of "normal" science, where it is no doubt that the phenomenon could be replicated; however, the replication process may not be straightforward since it requires a good understanding of the physics behind it, as well as good technical skills. In this article, two laboratory cases of experiments on laser physics are presented: the first one deals with a Nitrogen N_2 laser with a Polloni excitation circuit, and the second one deals with a transversally excited TEA carbon dioxide laser. For the nitrogen laser, it will be shown that reproducibility failed, and therefore, the reported experiment cannot be taken as a valid contribution to the advancement and understanding of nitrogen laser physics and technology. On the other hand, for the case of the TEA carbon dioxide laser, several comments are presented on the development of this finally successful experiment. Both cases show the importance of being technically up-dated in order to reproduce or improve the results reported by other researchers. Finally, a discussion about: What can we learn about the research practice from these two cases? It is presented, as well as the conclusions about the case studies; we hope they may be useful to philosophers of science and young scientists alike.

Keywords

Philosophy of Science, Replicability, Lasers

1. Introduction

It is accepted that modern science was born in the early seventeenth century when facts were taken as their basis. Before then, facts were not seriously taken as the foundation of knowledge; this was based on the authority of philosophers such as Aristotle or on the Bible. Many books have been written about "this thing called science", such as Chalmers's (1999) or about the rationality of science, such as Newton-Smith's (2002), and several anthologies on the philosophy of science have been published (e.g., Papineau (1996), Curd & Cover (1998), Klemke et al. (1998) and Psillos & Curd (2014)).

Most scientists accept that a theory is scientific only if it is verifiable, and we say that a theory is verifiable only if it is possible to deduce observational statements from it; instead, Popper would say that a theory must be falsifiable, but most important thing is that we must rely on facts. As we know, this is part of the central core of the education process of any scientist in the world. One of the most important characteristics of modern science is its replicability and objectivity. This means that a scientific result is taken as such only when it has been reproduced by other scientists. Indeed, the replicability of a scientific result in an objective and independent way by members of a scientific community is the cornerstone of science. We may say that a result is replicable when it can be carried out again, and the replication will successfully produce the same or a very similar result as the original. It should be underlined that this refers primarily to "hard sciences"; otherwise, it couldn´t be correct because it implies an absurdly too narrow definition of science and fields that are clearly sciences would be ruled out as pseudoscientific. This is so because not all sciences are experimental sciences. One such class would include anthropology, meteorology, and population biology wherein scientists in the field make detailed observations that take place at specific places and specific times under specific conditions that are not replicable. Another class is historical sciences, e.g., cosmology, geology, and evolutionary biology, where the science studies the evolution of a large-scale system that again is not replicable.

In this article, and largely due to the professional experience of the authors, two laboratory cases of experiments about laser physics are presented. The first one deals with a failed case of replicability of a Nitrogen N_2 laser with a Polloni excitation circuit, and the second one deals with a successful case of replicability of a transversally excited TEA carbon dioxide laser. At this point, it is important to mention a standard distinction that should be employed between wrong science, bad science, and pseudoscience. Wrong science is good science; well done that provides a warrant for belief in a theory that turns out not to be true. Consider Haley's comet as evidence in favor of the Newtonian laws of motion and gravitation. It is good evidence, yet, as we found out from Einstein, Newton's theory is false. We do not want to say that Newton was doing bad science. It was good science that turned out to be wrong. But there is bad science. Bad science is not pseudoscience. It is a scientist or team conducting legitimate science, but they do so in a way that is flawed and ought not to be repeated. Finally, there is pseudoscience which is non-science dressed up to falsely convince people it is real science.

The structure of this paper is the follows. In the next section, a brief introduction to some of the most important formal characteristics of science are discussed, as well as the differences between scientific and nonscientific undertakings; therein, our attention will be focused on replicability and its importance for the scientific endeavor in particular in laser physics. The following two sections present two laser physics cases: for the nitrogen laser, it will be shown that reproducibility failed, and therefore, the reported experiment cannot be taken as a valid contribution to the advancement and understanding of nitrogen laser physics and technology; on the other hand, for the case of the TEA carbon dioxide laser, several comments are presented on the development of this successful experiment. Finally, a discussion and conclusions about the case studies are presented; hopefully, they will prove to be useful to philosophers of science and scientists alike.

2. Replicability in Science

Several characteristics distinguish scientific activity from non-scientific activity. Paul Thagard (1998), in an interesting and amusing article, "Why Astrology is a Pseudoscience", clearly illustrates these differences. The first difference to notice between a non-scientific activity, such as astrology, and laser science is that the first one is incapable of making precise predictions, whereas a laser scientist can, for example, accurately predict the emission wavelength of a laser, even before he actually builds it, and to do this, he uses quantum mechanics theory applied to the laser active media. On the contrary, an astrologer would be unable to make similar precise predictions about anything; in fact, he does not even have solid theoretical tools to make any prediction.

Thagard proposes the following demarcation principles for scientific and non-scientific activities:

A theory or discipline which purports to be scientific is pseudoscientific if and only if:

1) *It has been less progressive than alternative theories over a long period of time and faces many unsolved problems; but*

2) *The community of practitioners makes little attempt to develop the theory toward solutions to the problems, shows no concern for attempts to evaluate the theory in relation to others, and is selective in considering confirmations.*

Thagard (1998: p. 71)

It is hoped that this principle captures what is most importantly unscientific about astrology, witchcraft, pyramidology and many other pseudosciences, but not of a scientific activity such as laser physics.

In practice, scientists observe what happens in the world and note regularities, they experiment with manipulating things so that they can be observed under special circumstances, and they also discover o postulate laws of nature that explain regularities and combine laws of nature into theories. In his everyday professional life, a scientist reads specialized scientific journals, which is important in order to be up to date with the newest scientific results and is also of great importance in order to propose, design and carry out new experiments. Depending on the measurements and results obtained in his experiments, he may confirm that he is on the right scientific track or that he is possibly doing something wrong. He must be constantly alert because in fact, a "right" experimental result may be irrelevant, whereas a "wrong" result may point out to a new and unexpected road or—sometimes—to a trivial mistake. *A priori*, it is not possible to know what the situation is; he must keep on working, testing different experimental alternatives, and he must keep on reading what other scientists from his area of expertise in the world are doing. For him, it will also be important to participate in scientific meetings; there, he will be able to talk to people who are interested in the same problems and will discuss how each scientist is solving particular problems or how other experimenters are setting up different experiments.

Replicability of scientific results means that those results are independent of any non-scientific and non-objective criteria such as the race, creed, color, nationality, geographic location of any scientist, group of scientists or their laboratories. Anybody, irrespective of who or what they are, in principle ought to be able to check for themselves, through their own experiments, that a scientific claim is valid. The replicability of scientific results is the cornerstone of scientific activity. In this sense, Collins states:

The acceptance of replicability can and should act as a demarcation criterion for objective knowledge.

Collins (1985: p. 19)

As we may see, replicability is a fundamental characteristic of scientific activity. Any non-scientific or pseudo-scientific activity does not possess this characteristic. Replicability is the Supreme Court of the scientific system. The importance of replicability was recognized by Popper, in his work *The Logic of Scientific Discovery*, as follows:

Only when certain events recur in accordance with rules or regularities, *as in the case of repeatable experiments*, *can our observations be tested –in principle- by anyone. We do not take even our own observations quite seriously or accept them as scientific observations until we have repeated and tested them. Only by such repetitions can we convince ourselves that we are not dealing with a mere isolated* "*coincidence*", *but with events which*, *on account of their regularity and reproducibility*, *are in principle inter-subjectively testable*.

Popper (1959: p. 45)

As we will see in the next two cases dealing with laser physics, this is indeed the case; however, we may ask, in general, what the criteria of science are, and by this, we mean the basic criteria used to distinguish science from commonsense knowledge, or at least, to distinguish what is scientific from what is unscientific. As we have previously seen, laser physics is scientific, whereas astrology is not, and one can provide many similar examples. Professor Herbert Feigel has proposed five criteria to distinguish science from non-science; these are listed by Klemke as follows:

1) Intersubjective testability. This means replicability, the possibility of verification by others, and therefore, also excluding beliefs from private, unique and unrepeatable experiences.

2) Reliability. This refers to that which when tested, turns out to be true.

3) Definiteness and precision. This refers to the elimination or vagueness and ambiguity. Here, measurement techniques are essential.

4) Coherence or systematic character. This refers to the organizational aspects of a theory; this also refers to the absence, or being free, from contradictions.

5) Comprehensiveness or scope. This refers to maximum explanatory power.

Klemke et al. (1998: pp. 32-34)

Even though some believe that those criteria are not correct or free from objections, they are usually accepted in daily activity by most scientists. It is also accepted that some of these five criteria may be absent except the first one, replicability, which as mentioned before, is the cornerstone of scientific activity.

It is worth noting that in 2016, a poll conducted by the journal *Nature* reported that more than half (52%) of scientists surveyed believed science was facing a "replication crisis" (Baker, 2016).

In the next section, two cases of replicability in laser physics will be described; the first one is a failed one, and the second is a successful one.

3. First Case: (Failed) Case of Replicability of a Nitrogen Laser

Nitrogen and excimer lasers are useful sources of pulsed ultraviolet light. In particular, before the modern upgrading of the diode, solid state and fiber lasers, nitrogen lasers were widely used in the pumping of dye lasers, fluorescence and spectroscopy studies, photochemistry, plasma diagnosis and high-speed photography, among other applications. The most common electric circuit used to pump these lasers is the double capacitor scheme called Blumline circuit, see Vazquez-Martínez & Aboites (1993). In this configuration, two usually flat capacitors are charged to a high voltage. Then, one of the capacitors is discharged through a spark gap, allowing the second capacitor to discharge through the main laser cavity. As is described in the above reference, the capacitors are made up of commercial 1.5 mm thick double sided copper circuit boards which can be charged up to 20 KV without dielectric break-down problems. The main discharge on the nitrogen filled laser cavity excites the nitrogen molecules, allowing them to emit ultraviolet laser radiation. The typical laser pulse width is 4 ns, with a maximum energy of 5.4 mJ and maximum efficiency (percentage of electrical energy converted to laser optical energy) of 0.81%. This is in contrast to most reported nitrogen lasers reported elsewhere, with typical efficiencies varying between 0.02% and 0.5%.

It must be stressed that in order to achieve the high efficiency of 0.81%, Vazquez-Martínez & Aboites (1993) had to carefully and systematically check most of the works previously published by other researchers (e.g., Iwasaki & Jitsuno (1982), Schwab & Hollinger (1976) and Fitzsimmons et al. (1976)), this in order to identify the contributions of each one on the individual components of a laser to achieve maximum peak power and efficiency; only with this information was it possible to design a laser by putting together the best results on laser design described by other researchers. For example, it was agreed that for better results, all inductance in the system, and specially the spark gap inductance, had to be minimized; therefore, a small inductance spark-gap was designed using a special geometry. In particular, it was known that Schwab had reported:

Given a fixed line capacitance, the voltage variation across the cavity is almost exclusively determined by the inductance of the spark gap switch. To obtain a high overvoltage across the cavity, a spark-gap with extremely low inductance is essential.

Schwab & Hollinger (1976)

In fact, this quotation is in agreement with the results also obtained by Iwasaki & Jitsuno (1982), who had experimentally and theoretically shown that the major limitation to increasing the laser output energy is the inductance of the spark-gap; the inductance of the discharge laser chamber has little importance, as long as the relevant inductance is kept below a certain value of about 10 nH.

We may see that the good efficiency obtained by Vazquez-Martínez & Aboites (1993) is mainly attributed to the low inductance present in the circuit, especially the low inductance of the spark gap. This allowed them to obtain short high-voltage waveforms across the laser cavity and therefore, an efficient excitation of the active molecular nitrogen medium; in fact, they reported shorter voltage waveforms than those of any other previous research work. Typical excitation voltage rise-times reported by previous authors were in the order of 25 ns, whereas with their design, Vazquez-Martínez & Aboites (1993) obtained shorter rise-times. Other parameters that were improved were the laser electrode profiles in the discharge cavity.

After experimenting with several electrode profiles, it was found that the "V-shape" design that was finally used improved the electron temperature and current densities of the discharge, therefore achieving higher population inversion and better laser emission. The previous account describes some important steps in the practice of scientific research, namely, the fact that researchers base their work on the results previously reported by other researchers. As we know, this is crucial to the advance of scientific research.

To the delight and amazement of world laser scientists, in 1986, a nitrogen laser with an astonishing 3% efficiency was reported by Oliveira dos Santos et al. (1986). Such a high efficiency contrasted with all the known efficiency results previously reported anywhere, which, as we have seen, usually varied between 0.02% and 0.8%. In their article, it was stated that:

This high efficiency was obtained by modifying the geometry of the discharge *capacitor and choosing capacitor and inductance values in the charge and excitation circuits in order to make resonant frequency in both circuits almost coincident.*

Oliveira dos Santos et al. (1986: p. 241)

Additionally, it was stated that: "The transmission line has been replaced by a coaxial capacitor concentric with [the] discharge tube". In this way, the discharge capacitor is a concentric one around the discharge laser tube, whereas the capacitor to fire the spark-gap remains outside the main laser. Sadly, since this article was published, nobody, no scientists or laboratory in the world, has been able to reproduce its results. An example of a published article trying to reproduce the results of Oliveira and co-workers, following as closely as possible the design and specifications therein given, was published by Pinto et al. (1991) providing an efficiency of only 0.11%, very far from the desired 3%.

Several years later, on November 12, 2013, in an answer given through the web site *ResearchGate* (https://www.researchgate.net/profile/Vicente-Aboites/questions) to the question "Does anyone have experience with the 3% Efficiency Nitrogen Laser?", Professor Vladimir A. Yamschikov, Principal Investigator of the Institute for Electrophysics and Electric Power, of the Prokhorov General Physics Institute of the Russian Academy of Science, called attention to his article "Efficiency of an electric-discharge N_2 laser", Apollonov & Yamshchikov (1997), adding the following comment (slightly edited here); "*I investigated in detail the efficiency of the nitrogen laser in the article: Apollonov & Yamshchikov (1997) "Efficiency of an electric-discharge N_2 laser" Quantum Electronics 27(6), pp. 469-442. There, it was shown that it is very difficult to obtain efficiencies higher than 0.1%. An efficiency of 3% is a measurement error! Don't spend your energy and time to prove the contrary*".

Oliveira dos Santos et al. (1986) article is a clear example of a non-replicable scientific result. Due to the non-replicable character of this result, it has no scientific value or interest at all; it is a useless and invalid result. Nevertheless, from the philosophy of science point of view, it is a very interesting result because it clearly illustrates the behavior of scientists within a scientific community: a result that cannot be replicated will be ignored by the scientific community. Of course, even when this is the case, several questions arise such as: How is it possible that such a large experimental error occurred? Given the enormous difference between the small known laser efficiencies and the large reported efficiency, did this not appear suspicious to the authors? It is known that in particle physics, superconductivity, quantum optics, and almost all other areas of physics, every result (especially a significant one) is doubly checked by other groups of scientists, and only then, it is accepted as a valid result worldwide. In this case, there was no confirmation of a 3% efficiency nitrogen laser anywhere, and therefore the result was sent into oblivion. We may wonder whose responsibility is replication? The sociological imperative in the face of such an anomaly is to publish as fast as possible. The reward structure of science is such that by publishing immediately, if the result is borne out, the team that achieved the anomaly is given priority for the breakthrough which will come with status in the community, awards, maybe even something named after them. But what happens in cases like this where the anomaly cannot be replicated? How ought we think of the science that generated the anomaly—is it wrong science or bad science? Should we think of the team that generated the anomaly as having failed to do science well or should we think that this sort of thing randomly happens even to the best of scientists? Should we condemn them for rushing to publication? Where does the responsibility for replication reside?

This may be just an example of "questionable research practices", which inflate the rate of false positives in the literature. Whatever the reason for an anomalous experimental result we may trust the scientific community. Wrong and bad scientific results will be exposed.

4. Second Case: (Successful) Case of Replicability of a TEA Carbon-Dioxide Laser

Collins (1985) discusses, in Chapter Three, the case of "Replicating the TEA-Laser", i.e., the situation when a scientist tries to repeat somebody else's work, stating that replicability is the touchstone of the common sense philosophy of science. H.M. Collins also discusses a paradox which he calls the "experimenter's regress", which arises when a scientist wants to use replication as a test of truth in the claims of scientific knowledge. Somehow, scientists are educated to believe that anybody ought to be able to check for themselves, through their own observations and experiments, that a scientific claim is valid. About this important topic Popper wrote:

Any empirical scientific statement can be presented (*by describing experimental arrangements*, *etc.*) *in such a way that anyone who has learned the relevant technique can test it.*

Popper (1959: p. 99)

The Carbon Dioxide Laser was developed by Patel (1964). These lasers operated at low pressure, the CO_2 gas mixture included nitrogen and helium, and it was excited with a Radio Frequency (RF) generator emitting infrared laser radiation al 10.6 microns, achieving continuous powers of 100 Watts. Six years later, Beaulieu (1970), in a Canadian defense research laboratory, reported the Transversely Excited Atmospheric Pressure (TEA) CO_2 Laser. In this TEA laser, electric arc formation was avoided, as well as the need to use a gas mixture and vacuum pumps to obtain the low pressure operation of previous lasers. His solution consisted of having a conducting bar facing a linear array of pins with a separation of a few centimeters; each pin was loaded with a resistor in order to force the discharge toward the conducting bar. To have a high voltage discharge, a short electric pulse had to be generated using a spark gap or a thyratron.

These first "Pin-Bar" TEA lasers, operating at around one pulse per second, were easy and cheap to construct. As mentioned, by operating at atmospheric pressure, complex vacuum and gas-handling systems could be avoided. They could produce MW peak powers of a few 100 ns duration capable of breaking down air if brought to a focus with a short focal-length lens. Disadvantages were poor gain symmetry, dissipation in the resistors and size.

In the early 70's Bealieu's laser was called the "origin" laser by many scientists trying to replicate it; some of the early attempts at replication are cited in the comprehensive review published by Foster (1972), see also, Pearson & Lamberton (1972). Initially, it was thought that no scientists succeeded in building a laser by using only information found in published or other written sources; however, hard experience showed that this is not the case. Facing difficulties and solving problems provided the technical experience necessary to, eventually, successfully build a laser. Clearly, sharing experiences and personal contact with other scientists was very important, and many indeed believed that this was essential for success. In fact, It was widely accepted that information from a "middle man" was necessary, i.e., information from someone who had already built a laser himself. In this sense, scientific exchange visits between different institutions were a standard activity. Collins summarizes this situation as follows:

In sum, the flow of knowledge was such that, first, it traveled only where there was personal contact with an accomplished practitioner; second, its passage was invisible so that scientists did not know whether they had the relevant expertise to build a laser until they tried it; and, third, it was so capricious that similar relationships between teacher and learner might or might not result in the transfer of knowledge. These characteristics of the flow of knowledge make sense if a crucial component in laser building ability is "tacit knowledge".

Collins (1985: p. 56)

Tacit knowledge is the term given by Polanyi (1958) to our capacity to accomplish skills without being able to explain how we do them. The typical example is the skill required for riding a bicycle, since no amount of analysis and study about the mechanics and dynamics of the bicycle will allow a beginner to get on and ride immediately. Likewise, a skilled rider will usually be unable to describe the dynamics and balance required. The rider simply does not know.

In Collins & Harrison (1975), the authors reported a study about the transfer of knowledge, where they discuss the construction of a TEA carbon dioxide laser which is also reported in Collins (1985). Many of the important technical problems found are explained in detail, such as arc breakdowns among the components, the probe coil, leads and tubes, anode marking and so on. Some of the problems there described would be surprising for most laser specialists of today, but at that time, it seemed that it was not obvious to the authors exactly where the problems were. For example, when discussing the length of the leads, they knew that the leads from the capacitors to the laser electrodes had to be short but had not given any quantitative consideration to those matters. It is reported that initially, the leads were about eight inches in length, which was considered "short by any standard". However, later on, they realized that the capacitor leads had to be considerably shorter than that, and then, they tried a length of six inches. However, electrical engineers and laser scientists know that this short length for the leads has to do with the inductance of the electric system, because in order to produce high voltage pulses with very short rise time, it is crucial to have a very small inductance. Essentially, the leads must have "zero" length, which implies that the capacitors and the discharge chamber have to be one besides the other, i.e., with electric contact, but without any electric lead in between. This is an example of the sort of knowledge that one may assume as not being capable of merely being acquired from a scientific article or report, or from an engineering electric drawing, which is a diagram that shows a continuous line to indicate an electric connection between the capacitors and the laser discharge chamber, even though in practice, there is no lead at all. The scholar must have enough basic knowledge and additional hands-on experience in order to correctly interpret an electric engineering blueprint. This example may seem rather naïve, because (as it was mentioned in the previous section about nitrogen lasers built since the sixties) electrical engineers and laser scientists, would know that a small length connection was essential to have a small induction. A second interesting but very disturbing example is the following: the authors reported some problems with the spark gap, and eventually, they had to check the polarity of the power source. After many trials, they realized that the electrodes were accidentally connected up the wrong way round. The power unit was providing +60,000 volts, instead of −60,000 volts.

The previous examples illustrate the fact that having a laser building ability requires not only technical information in the form of an article or a report but also the experience usually gained through years of practice and many failures. The authors learned that they lacked laser building abilities from the simple fact that the laser did not work until all the technical problems were correctly solved. An important conclusion drawn by the authors is that "the only indicator that someone has laser-building ability is his or her ability to build a laser".

5. What Can We Learn about the Research Practice from These Two Cases?

In many areas of science, we find that a scientific result is accepted by a scientific community only after it has been replicated. As recognized by Karl Popper, replicability is the Supreme Court of the scientific system. A clear example is the case of high energy physics where a new particle is only accepted by the scientific community when the experimental result of its detection has been replicated by other research groups around the world, see for example, Riordan (1992). Another interesting example is found in the study of meta-materials. Víctor Veselago (1968) proposed that there may exist materials with negative permittivity and permeability, therefore materials with a negative index of refraction. This idea was nothing else but a mathematical curiosity for 32 years till Smith et al. (2000) created the first device, called meta-material, with a negative index of refraction. This result was immediately replicated by many laboratories around the world due to its revolutionary applications including optical invisibility.

The two examples presented in this article deal with laser physics. The first example, of the failed replication of a Nitrogen N_2 laser with a Polloni excitation circuit, is difficult to explain. How could an experienced group of scientist obtain such a mistaken value for the efficiency of the constructed laser? How is it possible that this result was not suspicious? Perhaps this bad scientific result can be explained based on extra scientific conditions which may have a sociological o psychological explanation. These conditions may be, for example, the urgency to publish (in many research institutions the income of a researcher depends on the number of scientific papers published), or the ego associated with making a worldwide scientific breakthrough; this may blind an objective examination of the experimental results. The second example, of the successful replication of a transversally excited TEA carbon dioxide laser, shows the importance of a solid scientific and technical background. The behavior of any laser can be correctly estimated by a professional laser scientist even before he builds the device. This is so because laser science is based on well-established and confirmed science and technology.

6. Discussion and Conclusions

The replication process is a fundamental part of the advancement of modern science and technology. In this article, two study cases on experimental laser physics are presented, one being successfully replicated and the other resulting in failure. Experimental laser physics is an example of "normal" science, where it is no doubt that the phenomenon could be replicated; however, the replication process may not be straightforward since it requires a good understanding of the physics behind it, as well as good technical skills. The help provided by someone who has already built a laser may accelerate and shorten the building time process, but it is not a substitute for hard work. Also, the careful and methodic reading of previous research articles is crucial in order to identify the main obstacles which need to be overcome.

Both cases show the importance of being technically up-dated in order to reproduce or improve the results reported by other researchers. On the other hand, the idea that laser building science and engineering may be a form of tacit knowledge is very disturbing. We may understand that a circus juggler or an Olympic BMX cyclist will be unable to explain the theoretical dynamics of his activity to other people, and we may also agree that providing this theoretical explanation for the first time will not allow anybody to do juggling or to ride a bicycle. However, to assume that the ability to build lasers is in any way similar to the tacit knowledge of a juggler or a cyclist is to ignore that anything a laser scientist does or does not do, has a measurable physical consequence on the device that he is building, and this consequence always has an impeccable and rational scientific explanation.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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