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Research Article

The revolution of design by programmable materials

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Abstract
Global technological transformations revolutionize the design process both in conceptual and technical senses and add new meanings to the area of design. The design parameters of past eras are incomparable with today's design parameters. To define and forecast revolutions, Grinin and Grinin (2013) put forward the theories of production revolutions and production principles, to classify global technological transformations. Today, humankind experiences the primary modernization stage of cybernetic revolution and according to forecasts will pass to third 'stage of self-regulating systems' within the 2030s and 2040s.
In the light of the information acquired by the production revolutions and the theories of production principles and in the context of industrial design, one discussed within this study the programmable materials, which can be accepted as the pioneer of self-regulating systems. In programmable materials, 4D printing technology that began to be developed in mid-2010, was analyzed. The scenarios on the future of 4D printing and programmable materials were included and forecasts were put forward to assume how these scenarios will affect the design profession. This study emphasizes the necessity of adapting the industrial design profession to the contemporary by broadening its scope, and questioning and renewing the context of the profession, with the emphasis on digitalization being at the forefront.

Keywords: Programmable Materials, Design Process, Production Revolution, Production Principles, 4D Printing.

INTRODUCTION

Since the beginning of the 21st century, Industry 4.0, Covid-19 and the accompanying isolation process, technological developments in digitalization, the development of the metaverse and the importance of digitalization in every professional field constitute the main topics of the current discussions. The definition of the industrial design profession and the development of its scope within the changing and developing dynamics are also among the research subjects of this study. To understand how global technological developments will change the design and implementation processes, the methods of the field of futures studies may be used.

Grinin and Grinin (2015: 120) have put forward production revolutions and production principles theories to define and forecast revolutions by classifying global technological transformations. Researchers argue that the final stage of the cybernetic revolution we are experiencing today will be defined as "self-regulating systems" which will presumably start towards the 2030s and 2040s and will end in the 2060s – 2070s. While Industry 4.0 may be a precursor to "self-regulating systems", it is unlikely to be the last step. 4D printing (4DP) and smart materials, which have been working in the field of programmable materials (PM) since the mid-2010s, may be the new heralds of "self-organizing systems". With the transfer of programming skills to physical objects, 4DP gives the ability to material objects to change form and function in response to external stimuli (Campbell et al., 2014: 1). The development and availability of 4DP technology and materials marks the beginning of a new era in design and changes in both the scope of the material objects and the definition of the designer.

In this study, using the theories of production revolutions and production principles, the role of technologies like PM and 4DP, which can be considered as the pioneers of self-regulating systems, and also the materials in the design process and the future of design within the forecasts will be investigated.

METHOD

In order to probe the transformation of design within the development of new technologies and materials, production revolutions and production principles theories of Grinin and Grinin (2015) have been examined by using the literature analysis method. Integration of PM, 4DP and its predecessor 3DP technologies into the design process is again examined through literature analysis and design examples were revealed. The data obtained were analyzed and evaluated by using the content analysis method.

The Definition and Structural Model of Production Revolution Theory

According to Production Revolution theory (Grinin and Grinin, 2015: 120) whole history can be divided into four periods, based on the major technological breakthroughs: Hunter-Gatherer, Craft-Agrarian, Trade-Industrial and Scientific-Cybernetic periods (Figure 1). Each period identifies the transition to a fundamentally new production system. Grinin and Grinin (2013) define production revolution as “a radical turn in the world productive forces connected with the transition to the new principle of management not only in technologies but also in the interrelations of society and nature. The difference of a production revolution from various technical overturns is that it touches not only some separate essential branches but also the economy on the whole.” (p. 101). According to the theory, Agrarian, Industrial and Cybernetic Revolutions had the most comprehensive and far-reaching consequences for the society.

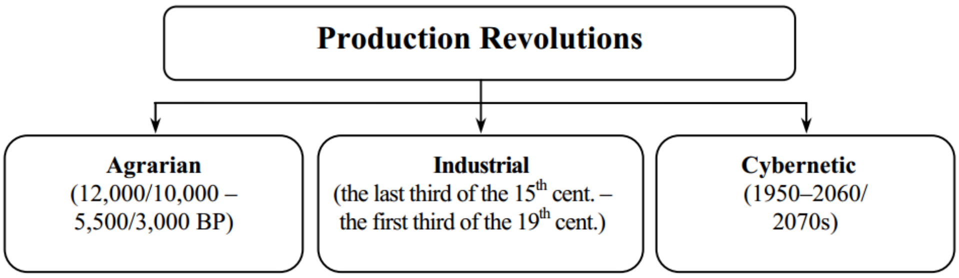

Figure 1. Production revolutions

Cybernetic Revolution have led to the emergence of information technologies, and in future will support the transition to use of self-regulating systems (Grinin and Grinin, 2015: 121). The theory proposes that each production revolution has an internal cycle and comprise of three phases: Initial Innovative Phase, Modernisation Phase and Final Innovative Phase (Grinin and Grinin, 2013: 101) (Figure 2).

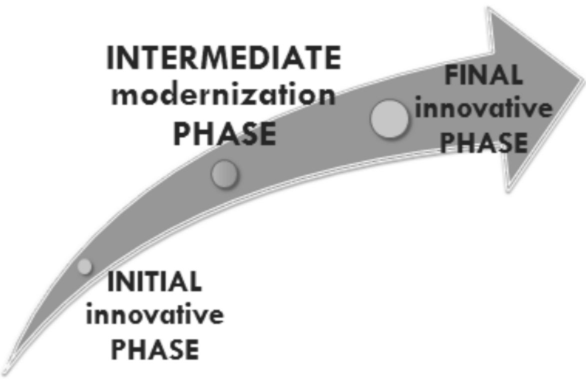

Figure 2. Phases of production revolutions

In the initial innovative phase, a new revolutionary production sector emerges. The second phase composes of diffusion, synthesis, and improvement of new technologies, based on the revolutionary production sector.

Finally new technologies mature to optimum features in the final innovative phase (Grinin and Grinin, 2015: 121).

The initial innovative phase of the Cybernetic Revolution comprises the years between 1950 and 1990s, especially in creation of electronic control facilities, communication, and information, besides the fields of automation, energy production, synthetic materials, space technologies, exploration of space and sea, and agriculture (Grinin and Grinin, 2016: 24). For the present, the humankind experiences the modernization phase of cybernetic revolution and according to forecasts will pass to final innovative phase, self-regulating systems, in the 2030s or 2040s (Grinin and Grinin, 2016: 25).

The Definition and Structural Model of Production Principle

Grinin and Grinin (2015) define the production principle as “a period of genesis, growth and maturity of new forms, systems and paradigms of organization of economic management, which surpass many times the former ones in major parameters” (p. 122). The production principle comprises of six stages, in which the three stages correspond to the phases of production revolution and the remaining three stages cover the development of the new production principle in the structural, systemic, and spatial sense (Grinin and Grinin, 2015: 122) (Table 1). The first phase is the beginning of production revolution, in which the new and not yet developed production principle emerges. The second phase is called as the primary modernization and comprises the period of strengthening the production principle. The production revolution completes in the third phase and the production principle acquires advanced characteristics. The production principle matures in the fourth phase and the wide geographical and sectoral use of new technologies triggers transformations in social and economic fields. In the fifth phase, the principle of production becomes widespread in the world, technologies are intensified, and opportunities are brought to the limit beyond which crisis features emerge. The sixth phase is called as non-system phenomena, or preparatory phase for the transition to a new production principle. The intensification of technology leads to emergence of non-system elements which prepare the birth of a new production principle (Grinin and Grinin, 2015: 123). The last three phases characterize mature features of the production principle.

Table 1. Production priciples’ phases

Production Principle	**1st Phase**	**2nd Phase**	**3rd Phase**	**4th Phase**	**5th Phase**	**6th Phase**	**Total Production Principle**
Scientific-Cybernetic	1955-1995/2000	1995-2030/40	2030/40-2055/70	2055/70-2070/90	2070/90-2080/105	2080/2105-2090/2115	1955-2090/2115

The Scientific-Cybernetic production principle has started the second stage in the 1990s and will pass to the third stage between 2030 and 3040s. The third stage is called as the self-regulating system and will last until the 2070s (Figure 3).

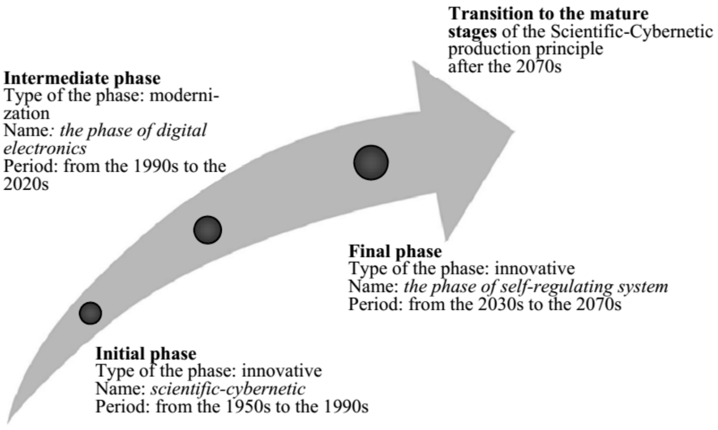

Figure 3. The phases of the Cybernetic Revolution

Self-regulating systems are the systems that operate with a small or non-human intervention and regulate themselves by responding in a pre-programmed and intelligent environment. The artificial Earth satellites or pilotless planes can be given as examples to self-regulating systems. According to Grinin and Grinin (2016: 45) a lot of self-regulating systems connected with biology and bionics, physiology and medicine, agriculture and environment will emerge during the final phase of the Cybernetic Revolution.

Programmable matter (PM), the science, engineering, and design of physical matter that has the ability to change form and/or function (shape, density, moduli, conductivity, color, etc.) in an intentional and programmable fashion can be given as examples to self-regulating systems (Campbell et al., 2014: 2). In the core meaning, computers that process pre-programmed information and diapers that can be pre-programmed to inflate according to the amount of fluid received are also programmable matters. Although programmable materials have been studied since the 1990s, the meaning and scope of the concept has changed since the mid-2010, by the rise of a new technologies like 4D printing.

3DP-Transition to 4DP

In order to better understand 4DP technology, it is necessary to examine its predecessor 3DP technology and its effects on design. In 1986 Charles Hull's patent (Hull, 1986) for a stereolithographic process marks the beginning of a new era. This patent marks the beginning of 3D printer technologies and the revolution that this technology has led in many sectors.

In 2017, the first architectural structure, The BOD (Building On Demand), was printed by the company COBOD with a 3D printer and a new era in building construction technology started (Figure 4).

Figure 4. The BOD (Building On Demand)

Again in 2017, the first residential building in Yaroslavl, Russia had been printed with a 3D construction printer by the company AMT-SPECAVIA (Figure 5).

Figure 5. The first residential building in Yaroslavl

In 2018, the company MX3D unveiled the world’s largest (the12-meter-long) stainless-steel 3D-printed bridge that took six months to print (Figure 6).

Figure 6. The MX3D algorithm bridge

4DP

A new disruptive technology, 4D printing, started to develop while 3D printer technology started to settle and became widespread. In addition to having the economic, environmental, geopolitical, and strategic effects of 3D printing, 4D printing (4DP) creates new expansions by transferring programming skills to physical objects. The fourth dimension in 4D printing refers to the ability for material objects to change form and function in response to external stimuli, whether a signal from a human or a reaction to changes in the environment (temperature, moisture, light, current, etc.) (Campbell et al., 2014: 1). The term of '4D Printing' was used for the first time by Skylar Tibbits during his 2013 TED talk, in which he presented self-assembling 3D-printed structures. Skylar Tibbits is a co-director and founder of the Self-Assembly Lab housed at MIT's International Design Center. The Self-Assembly Lab focuses on self-assemblies and programmable material technologies for novel manufacturing, products, and construction processes. The Self-Assembly Lab's 2D surface that self-transforms into a rigid surface cube without human intervention, can be given as an example to 4D printing technologies (Figure 7).

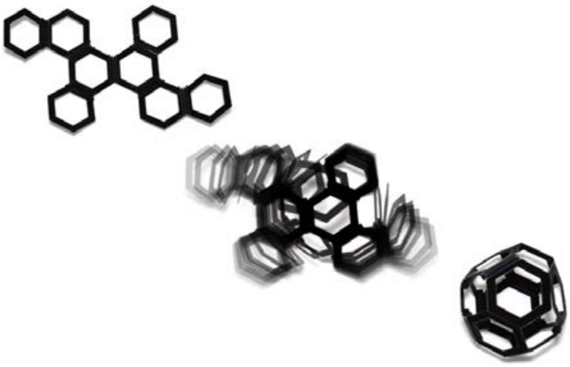

Figure 7. A 2D Surface that Self-Transforms into a Rigid Surface Cube

According to Campbell et al. (2014: 11) 4DP offers the potential of recyclability, unique actuation and sensing, and multiple functions/reconfigurations for products. 4DP brings movement and performance to physical objects by enabling them to shape-shift from one form to another consciously. Andreoletti and Rzezonka (2016: 13) suggest shifting the concept of "programmable" with "processual", and state that replacing the concept shifts the primary interest towards the alterability and the temporal qualities of materials. Besides, the concept of ""programmable" implies the code dictating to passive matter, "processual" defines a relationship between maker, syntax, user, form, and material as an open process of influencing agents" (Andreoletti and Rzezonka, 2016: 13).

4DP Materials

While the properties of existing materials had supported the development of 4DP technology, this new technology has also led to the creation of new materials. Although programmable materials are designed with high performance in mind, they are as cost-effective and easy to manufacture as traditional materials and also more advantageous than traditional materials due to their disassembly and self-assembly features (Ramesh et al., 2018: 9). These programmable new materials are: self-transforming carbon fiber, printed wood grain, custom textile composites, hydrogel, shape memory polymer fibre and other rubbers/plastics.

Smart materials have many functions such as self-sensing, responsiveness, shape memory, self-repair, self-adaptability, and multifunctionality, and they can be classified into two basic categories: shape-memory materials and shape-changing materials.

Shape memory materials are capable of returning from the transient shape to its original shape when stimuli are applied. Shape memory materials include shape memory alloys, shape memory polymers, shape memory gels, shape memory ceramics, and other shape memory hybrid materials. Shape-changing materials are transformed in response to the stimuli, and when the stimuli are removed, they return to their permanent shape (Pei and Loh, 2018: 96). Pei and Loh (2018: 105) emphasize the importance of having a grasp of the transformational properties of smart materials and highlight one of the main challenges in the field of 4DP as programming the parts successfully in order to achieve the desired transformational change at a given location. Different smart materials have different transformational properties, and these properties require different programming inputs or stimulus. Some of these transformational properties can be listed as follows: one-way shape memory effect, two-way shape memory effect and three-way shape memory effect (Pei and Loh, 2018: 98).

In one-way shape memory effect, the object is permanently deformed when the external stimuli is applied. In order for the object to return to its original state, a programming phase is required (Pei and Loh, 2018: 99). Cooling of an object, that uses temperature as a stimulus in the 4th dimension, to return to its original state after being deformed, can be given as example (Figure 8).

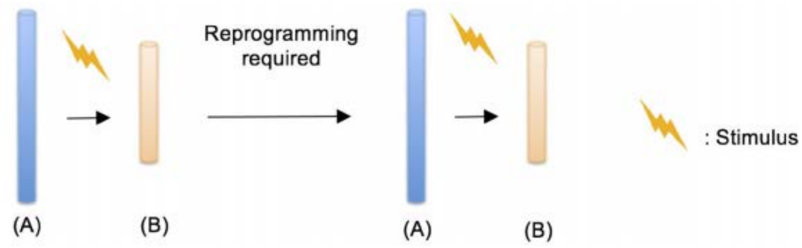

Figure 8. One-way shape memory effect

In two-way shape memory effect, the material is exposed to the stimulus, and it has the ability to remember two different shapes without the need for an external stimulus (Pei and Loh, 2018: 99) (Figure 9).

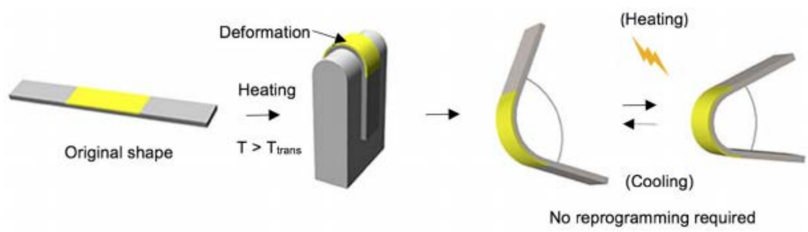

Figure 9. Two-way shape memory effect

In three-way shape memory effect, the material has an intermediate shape other than the original and temporary shapes. If there is more than one intermediate shape, then this condition is called as multiple shape memory effect. In addition to all these features, there are 4D heterogeneous materials composed by using multiple smart materials together (Pei and Loh, 2018: 99) (Figure 10). These objects are designed by using different properties of various smart materials.

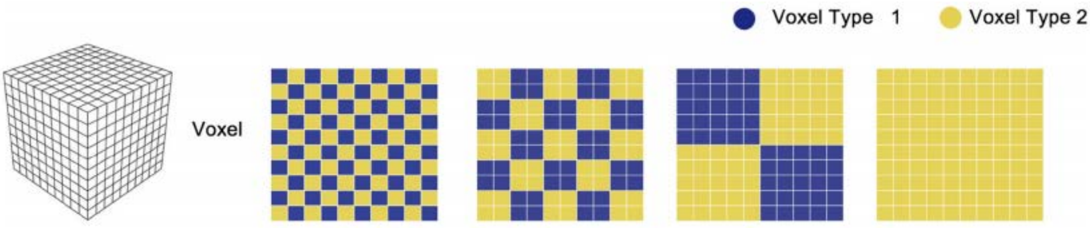

Figure 10. Heterogeneous 4D printed objects

Design Projects Supported by PM and 4DP

Programmable Table

The Programmable Table is a furniture designed with the 4D technology in cooperation with MIT's Self-Assembly Lab and Wood-Skin S.r.l., in order to solve volume problems in shipping and re-assembly stage. It has a flat structure in order to reduce the volume in the shipping process, and has the ability to reach its 3-dimensional form without the need for human power when it is removed from its packaging (Self-Assembly Lab, 2022) (Figure 11).

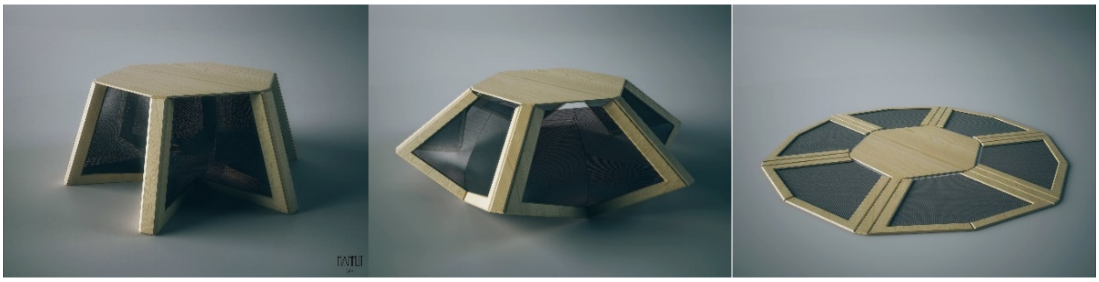

Figure 11. Programmable Table

Ultra Personalized 4D Printed Shoes

The ultra personalized 4D Printed Shoes are fully personalized printed high heel shoes in a period of two months for a single user (Nachtigall et al., 2018: 1). The shoes were designed with the advance of 4DP to fit the user while they move and change. The designers highlight the key design considerations as: aesthetics, comfort, robustness, balance, and temperature (Nachtigall et al., 2018: 2) (Figure 12).

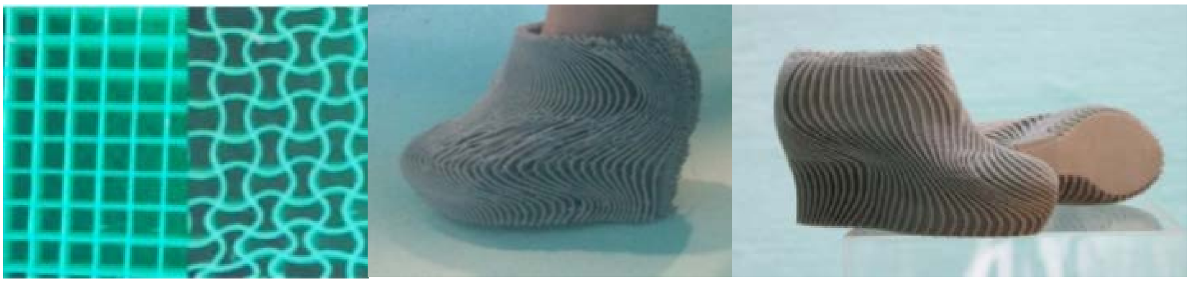

Figure 12. Flexible material sample and finished product

HygroSkin

The project HygroSkin – Meteorosensitive Pavilion was first shown in the exhibition ArchiLab 2013. HygroSkin is a climate-responsive architecture, in which the architectural skin autonomously opens and closes in response to surrounding humidity without requiring any kind of mechanical or electronic control. The modular planar plywood sheets response to weather and self-form to form conical surfaces (Menges, 2013) (Figure 13).

Figure 13. The project HygroSkin - Meteorosensitive Pavilion

Chrysalis Gemini

The project "Chrysalis Gemini" interrogates the human-material interaction by the development of programmable or smart materials. "Chrysalis Gemini" is a ceramic design with self-healing abilities. In the project, microencapsulated healing agents that are embedded into the structure of ceramic, react, and fill the gaps composed by a crack or a rupture (Andreoletti and Rzezonka, 2016: 8). As the designers aimed to create a sensorial memory, the food and drink contained after the healing process leave traces in the ceramic, by the advance of the agent to absorb flavour and colour (Figure 14).

Figure 14. Chrysalis Gemini

FINDINGS

With the development of the 3DP technology, opportunities have emerged in areas such as: prototyping in the design process, fast and on-site production opportunities, easy access to the object and personalization from the user's point of view. Felek (2019: 295) suggests that 3D printers can be used for post-disaster sheltering, especially in countries with housing shortages, in the production of buildings with geometry that cannot be produced with traditional methods, and even in order to create a life form outside the world. PM and 4DP technologies have broaden this development to a new perspective. As seen in the examples given in previous sections; 'a self-forming furniture' is able to avoid packaging, storage, and installation processes; or with a pair of 'personalized' shoes, the most suitable shoes for the user's feet can be designed to achieve the best performance; structures that can change their form by self-controlling humidity can be built; or sensorial memory can be built with self-healing materials. Apart from these examples, it is stated that projects such as aircraft wings that change shape and aim for the best performance, pre-programmed tires with better road grip, roads and bridges that can adapt themselves according to load lifting conditions and weather can be realized.

The researchers state that these studies use very little of the advanced technology and the technology promises much more. Campbell et al. (2014: 4) state that in the future, voxels will replace today's production methods with the developing PM and 4DP technologies. Voxels are basically interpreted as the proteins that make up the biological life. Just as basic proteins provide for the formation of all kinds of biological life, voxels can also come together in various combinations to form various forms. It is envisaged that voxels will form our future physical object’s world with different combinations, just as Legos come together to form new forms. The development of Voxel technology may be defining the maturity processes of the self-regulating systems phase. Today, there are some challenges for the voxel technology to reach maturity: design, material, adhesions between voxels, energy, electronics, programming, adaptability to different environments, assembly, standardizations, certifications, physical and cyber security, affordable manufacturing techniques, characterization, and recycling (Campbell et al., 2014: 8). Although all these topics concern the design profession, the main question is what competence should the designer have while designing with voxels.

CONCLUSION

Self-regulating systems are systems that operate with little or non-human intervention and regulate themselves by responding in a pre-programmed and intelligent environment. Regardless of the predictions made on PM and 4DP, Grinin and Grinin (2016: 45) state that many self-regulating systems related to biology and bionics, physiology and medicine, agriculture and environment will emerge in the final stage of the cybernetic revolution. It is stated that the biggest self-regulating system project, independent of objects, is biological, and therefore artificial intelligence, bio-technologies and nanotechnology fields will come to the fore in cybernetic revolution. As at the beginning of the article, "digitalization", which has been one of the most popular discussion topics of modern-days, is becoming the main focus again. Whether the subject is the Metaverse or the future self-regulating systems, the designer will not be able to meet the design needs of the future with today's design understanding, methods, and competencies. The name of the profession, which was transferred from industrial product design to industrial design, will be able to find a place for itself in the future, perhaps by pullulating with new contexts or perhaps by revolutionizing the profession.

Authors' Contributions

The author contributed to the study 100%.

Competing Interests

There is no potential conflict of interest.

Ethics Committee Declaration

Ethics committee declaration was not required for the study.

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