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# Investigation And Simulation of Dielectric Elastomer Actuators Used in Artificial Muscle Applications

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**Abstract:** Dielectric Elastomer Actuator (DEA) consists of a thin dielectric elastomer membrane sandwiched between two electrode layers. When low current high voltage is applied to the two conductive layers, opposite loads occur on the surface which tends to pull one another. This voltage application causes thinning in width and expansion in surface area. DEAs are the favorite subject of research due to their low-cost advantages, fast response, high energy density, wide deformation, and softness. Due to the rigidity of the electric motors and the metal components of the robot, soft-acting robots using DEA are preferred to perform complex tasks instead of conventional robots. Robots with DEA have higher flexibility and better adaptability. Therefore, soft robots are popular topic in robotics research. DEAs are the best candidate materials for next-generation soft robot actuators and artificial muscles. In this study, simulation of the robotic systems has been realized by using DEAs calculation methods. Simulation results were compared with the data obtained from the application. This study will be the source of future studies on the subject. In the simulation, Matlab 2016 student and Labview Home and Students programs were used.

**Keywords:** Artificial muscle, electro-active actuator, soft actuator, dielectric elastomer, electromechanical efficiency, conductive elastomer.

# Yapay Kas Uygulamalarında Kullanılan Dielektrik Elastomer Aktuatörlerin İncelenmesi ve Simülasyonu

**Öz:** Dielektrik Elastomer Aktüatör (DEA), iki elektrot tabaka arasına sıkıştırılmış ince bir dielektrik elastomer membrandan oluşur. İki iletken tabakaya düşük akımlı yüksek gerilim uygulandığında, birbirini çekme eğiliminde olan yüzeyde zıt yükler meydana gelir. Bu da eninde incelmeye ve yüzey alanında genişlemeye yol açar. DEA'lar, düşük maliyet avantajları, hızlı tepki, yüksek enerji yoğunluğu, geniş deformasyon ve yumuşaklık gibi özellikleri sebebiyle araştırma konusudur. Robot üretim teknolojisinde kullanılan elektrik motorları ve robotun metal bileşenlerinin sertliği sebebiyle, karmaşık görevleri yerine getirmek için DEA kullanan yumuşak mekanizmalı robotlar tercih edilir. DEA özellikli robotlar daha yüksek esnekliğe ve daha iyi uyarlanabilirliğe sahiptir. Bu nedenle, yumuşak robotlar robotik araştırmada popüler konulardandır. DEA'lar gelecek nesil yumuşak robot aktüatörleri ve yapay kaslar için en iyi aday malzemelerdendir. Bu çalışmada, DEA'ların hesaplama yöntemlerinden faydalanılarak simülasyonu gerçekleştirilmiştir. Simülasyon sonuçları uygulama neticesi elde edilen verilerle mukayese edilmiştir. Konuyla ilgili bundan sonraki yapılacak çalışmalara kaynak olabilecektir. Simülasyonda Matlab 2016 student ve Labview Home andStudents programlarından faydalanılmıştır.

**Anahtar Kelimeler**: Yapay kas, elektro-aktif aktüatör, yumuşak aktüatör, dielektrik elastomer, elektro-mekanik verimlilik, iletken elastomer.

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## 1. Giriş

Dielectric elastomer actuators (DEA) are materials that convert electrical energy into mechanical energy and the advantages of these materials are being lighted and having flexible energy density. Conventional robots are typically driven by hard actuators, while biological entities are mostly made up of soft muscles. Being soft gives compatibility function, so greatly increases the range of activation time and degrees of freedom. An active polymer whose voltage level can be controlled by a potentiometer linearly exhibits sensitive electromechanical behaviour [1-7]. The dielectric elastomer actuator (DEA) is categorized as an electro-active polymer (EAP) having great deformation ability and rapid responses. DEAs are capacitors that deform with high voltage. At the same time, DEAs continue to be developed as sensors or generators. Depending on the high voltage, electrical charges of the opposite poles accumulate on the membrane of the dielectric elastomer, resulting in a decrease in membrane thickness and an expansion of the membrane surface. As a result of this expansion, deformation occurs and starts to work like an artificial muscle [2,8].

Although DEA has many outstanding mechanical and physical properties, one of its most important features is reliability due to its fully covered edge. In addition, both the ease of production and the fact that it can be multi-layered is one of its other prominent features [22-23].

DEAs are a new technology inspired by biological creatures found in nature and they can be used as artificial muscles in medical, military and industrial applications. For this reason, conventional robots can be replaced by DEAs that converts electrical energy into motion energy. DEAs are promising for the future because they have similar properties to human muscles due to the advantages of high energy density, lightweight, high yield cost, low elasticity. DEAs are used not only as actuators but also as sensors [9]. These materials have been used in many fields such as robots and artificial muscles for prostheses in the biomedical field [10,12]. Also DE deforms under tension and performs a mechanical reaction. In addition, with its structure resembling a living muscle of the DE, the applied voltage acts like a sensor with its capacitance size [24-26].

DEAs generate a static charge at a high voltage, which causes thinning of the elastomer's membrane under the influence of Maxwell's pressure and an expansion in the membrane's surface. Such materials are compatible with natural muscles [2,13]. The electrical energy that energizes this working mechanism is transformed into motion energy and causes big deformation [14,15]. The electromechanical pressure (Maxwell) acting on DEs can be calculated as in the following equation;

$$p = \varepsilon_r \, \varepsilon_0 \, E^2 = \varepsilon_r \varepsilon_0 (V/t)^2 \tag{1}$$

Where $\varepsilon_r$ is the dielectric constant, $\varepsilon_0$ is the free field permeability (8.85x10-12 F / m), E is the electric field, $V$ is the voltage, and t is the dielectric elastomer thickness. This equation also known as the maxwell pressure can be calculated by using elastomer in-plane elongation and vertical contraction. By mechanically compressing the membrane in terms of thickness, an expansion occurs in each direction of the plane of the membrane. The thickness tension based on Hooke's law can be written as follows:

$$s_z = -p/Y = -\, \varepsilon_r \varepsilon_o V^2/(Yt^2) \tag{2}$$

$Y$ is the modulus of elasticity of the composite film with polymer electrode called Young's modulus, it is the material module that defines the hardness of the material. The Young modulus is a measure of the ability of a material to withstand length changes under longitudinal tension or compression. Stress ratio $\lambda = \varepsilon_r \varepsilon_o / Y$can be written as in the equation. The effect of this stress on the material can be defined by $\varepsilon_z = -\lambda E^2$.Dielectric elastomer materials consist electric field on themselves like a capacitance. This capacitance, $C = \varepsilon_r \varepsilon_o A/t$ equation A is shown by conductor field, C capacitance [16,17]. Since the structure of this material used is assumed to be incompressible $(1 + \varepsilon_x)(1 + \varepsilon_y)(1 + \varepsilon_z) = 1$, total area of deformed material is found as Salan = $(1 + \varepsilon_x)(1 + \varepsilon_y) - 1$ [17].

In recent years, silicon and acrylic polymers used in DEAs have been studied [1]. Pelrine et al. focus on working on materials with a high dielectric constant, low elastic modulus, and distortion-resistant materials. After identifying such polymers, they calculated the occurred stresses with many tests. As a result of the studies performed, it was observed that the pre-stretch of the polymers used significantly increased the working performance [2].

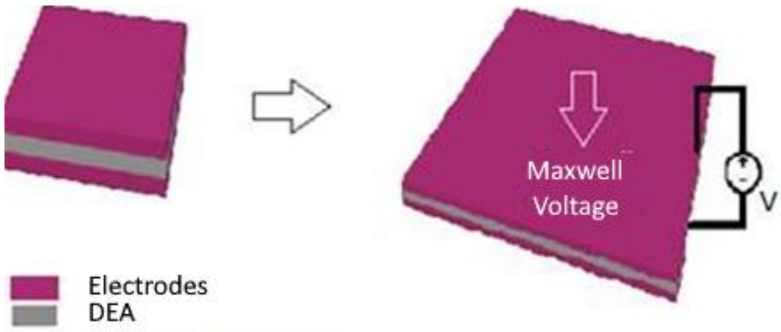


**Figure 1.** Operating mechanism of the dielectric elastomer actuator.

Dielectric elastomers, which are members of electroactive polymers, deformation occurs when electric field is applied. These polymers are of interest as robots, surgical device and artificial muscle design. There are still many areas of study for these polymers, which have undergone great deformation in recent years. In this study, simulations of the change resulting from the deformation caused by the change of voltage and pre-strech were carried out. Pre-stressing and tension appear to directly affect the deformation of the dielectric elastomer. As a result of the simulation, the use of appropriate pre-tension and tension will be beneficial in the use of the studies to be done.

In this study, 3M VHB4910 and 3M VHB4905 materials, known as dielectric elastomers, are studied on their application areas, methods and their characteristics and their simulations in artificial muscle actuators. Our work is to model a planar actuator and simulate changes in a thickness direction of displacements when high DC voltages are applied to the electrodes.

One of the most difficult tasks encountered in this application is to supply the DEA with high voltage ranging from 1kV to 10kV. However, the application of this high voltage to DEAs does not pose any safety concerns due to their ability to operate at low currents. DEA both pre-stress and stress appear to affect the characteristics of the material. For this reason, the results of experiments and simulations conducted in this study show that; In order for DEA to be used as robotic, surgical and artificial muscle, appropriate tension and pre-stretching ratios must be determined. If the pre-stress is high at the desired deformation rate, it decreases at the given stress. Excessive pre-tension and high tension damage the DEA. Maxwell pressure and displacement data (dispacement) occurring in DEA due to pre-tension and tension were obtained by simulation.

## 2. Material Method and Fabrication

Commercially produced materials commonly used in DEAs are known as BJB Enterprises TC-5005, 3M VHB-4910, and NuSil Technology's CF19-2186. Dielectric elastomers are very suitable for use as actuators with lightweight, high flexibility and reasonable response time. VHB-4910 acrylics have been reported to exhibit more viscoelastic characteristics and higher leakage currents than silicone polymers [18].

Dielectric elastomer actuators generate a strong electric field and at the same time, high voltages are needed to activate these materials. Electrically charging electrode coated insulating material with a high DC voltage power supply is the operating system of the DEAs. This electrical charge causes electrostatic deformation.

In these experiments, DE 30mm x30mm pre-stretching process was performed at 15mm x15mm diameters. An electric field is applied to the 10mm x10mm surface in the center of the DE. The simulations of the deformations occurring under pre-tension and tension of the experiments were carried out. Dielectric elastomer materials are generally composed of acrylic, silicone or polyurethane. Commonly acrylic VHB4910 and VHB4905 are a type of double-sided adhesive tape that has good adhesion and produces high deformation [21]. Since these bands are elastic, pre-tensioning can be applied. Conductive carbon grease (Premium Carbon Conductive Grease, MG Chemicals), which is widely used in the literature and acts as an electrode, was brushed on both surfaces due to its good adhesion to the elastomer, excellent electrical conductivity, low resistance and affordable price.

Typically, silicon or acrylics are used as dielectric elastomer materials. Materials such as graphite powder, carbon powder, or carbon oil are preferred to provide electrical conductivity. Although the operating voltage of the DEAs is high (~ 1-10 kV), its current is less than a few milliamps, leading to very little operating power. The activation strain can be obtained over 100% deformation [19].

One of the most difficult tasks encountered in this application is to supply the DEA with high voltage ranging from 1kV to 10kV. However, the application of this high voltage to DEAs does not pose any safety concerns due to their ability to operate at low currents. In addition, since it works with dc-dc converters, it allows it to be controlled by electronic circuits. In order to use DEA in surgical and practical applications, it is necessary to know under which conditions the deformation change should be kept. To control DEAs, a high dc voltage, a low current, and a control unit are needed as shown in figure 2 This determines how often and how much electrostatic pressure the actuator will need to be obtained.

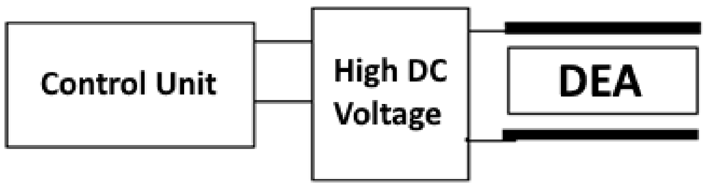


**Figure 2.** Block diagram of the working mechanism of DEAs

Firstly, in a dielectric elastomer, areas of the electrodes expand and electrodes become closer due to a decrement in film thickness. As they approach each other, opposing charges approach each other and convert electricity into mechanical energy [1]. When the DEAs are connected to a circuit, as seen in figure 3, the electrons in the elastomer are spread dispersedly, while bending or expansion occurs at the positive end of the high voltage.

In these experiments, DE 30mm x30mm pre-stretching process was performed at 15mm x15mm diameters. An electricfield is applied to the 10mm x10mm surface in the center of the DE. The simulations of the deformations occurring under pre-streching and tension of the experiments were carried out. Dielectric elastomer materials are generally composed of acrylic or silicone polyurethane. Commonly acrylic VHB4910 and VHB4905 are a type of double-sided adhesive tape that has good adhesion and produces high deformation [21].

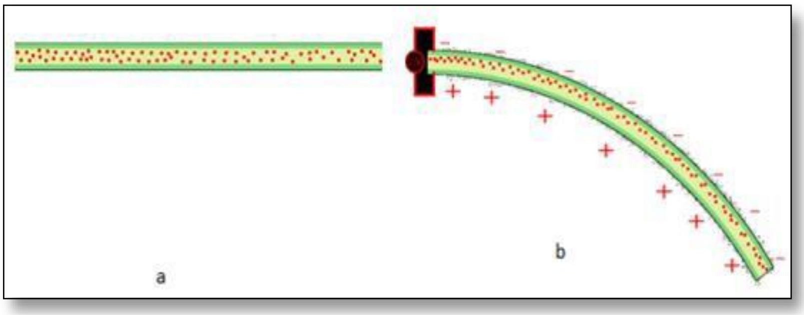


**Figure 3.** Operating response of the dielectric elastomer actuator

Since these bands are elastic, pre-streching can be applied. Conductive carbon grease (Premium Carbon Conductive Grease, MG Chemicals), which is widely used in the literature and acts as an electrode, was brushed on both surfaces due to its good adhesion to the elastomer, excellent electrical conductivity, low resistance and affordable price [21].

## 3. DEA Simulation and Numerical Analysis

One of the widely used dielectric materials in the literature is acrylic and the other is silicone elastomers. These materials have different advantages and disadvantages over each other. Acrylic elastomers can produce up to 380% greaters train than silicone elastomers and have high dielectric constants. Silicon eelastomers, on the other hand, have high electromechanical response speed, high working temperature, and high energy efficiency [20]. Due to theease of application, silicone materials have a wider range of applications than acrylic materials in solid form. In recent years, studies have been carried out in the field of DEA modeling and simulation. These are physical-based modeling [27] performed in a multi-layered DE. As a result of the three-dimensional modeling of DEA by applying high voltage, the time dependent mechanical reaction has been measured [28]. In addition, for the design of soft machines, the static and dynamical response of a multilayer DEA is analyzed by simulating a mechanical model [29]. Prechtl et al. A multi-degrees-of-freedom dynamic model is presented to ensure good performance of DEA [30]. In this study, the reaction of a circular DEA, the formation of the maxwell tension, the amount of displacement obtained and the reaction of the pre-tension have been simulated.

Modeling of the dielectric elastomer actuator was performed in Matlab 2016 student and Labview Home andStudents programs. In the performed simulation, the dielectric constant ($\varepsilon_r$) is given 4.7 for VHB4910 and 4.5 for VHB4905, free field permeability ($\varepsilon_o$) is given 8.85x10-12 F/m, strain limit ($J_{lim}$) is given 120 and strain shear modulus is given 25.4 kPa, these are standard values that used in simulation and it is shown in Figure 4. In this simulation, the input voltage varies between 0 and 5kV and the result of the simulation is illustrated in Figure 4.

The values obtained in these programs were also examined and simulated in a MATLAB environment. These values show that the DEAs known as artificial muscles are compatible with elastomeric materials. DEAs have varying dielectric constant and different vacuum permeability. In figure 5, the relation between the volt of the pressure in the maxwell equation is illustrated by applying 0 to 5kV to 3M VHB4910 and 3M VHB4905.

When dielectric elastomer actuators are connected to the circuit, displacement results occur as a response to applied 0 to 5kV input voltage is shown in figure 6. This illustration shows displacement away from the center point according to input voltage and expansion obtained with the maxwell pressure.

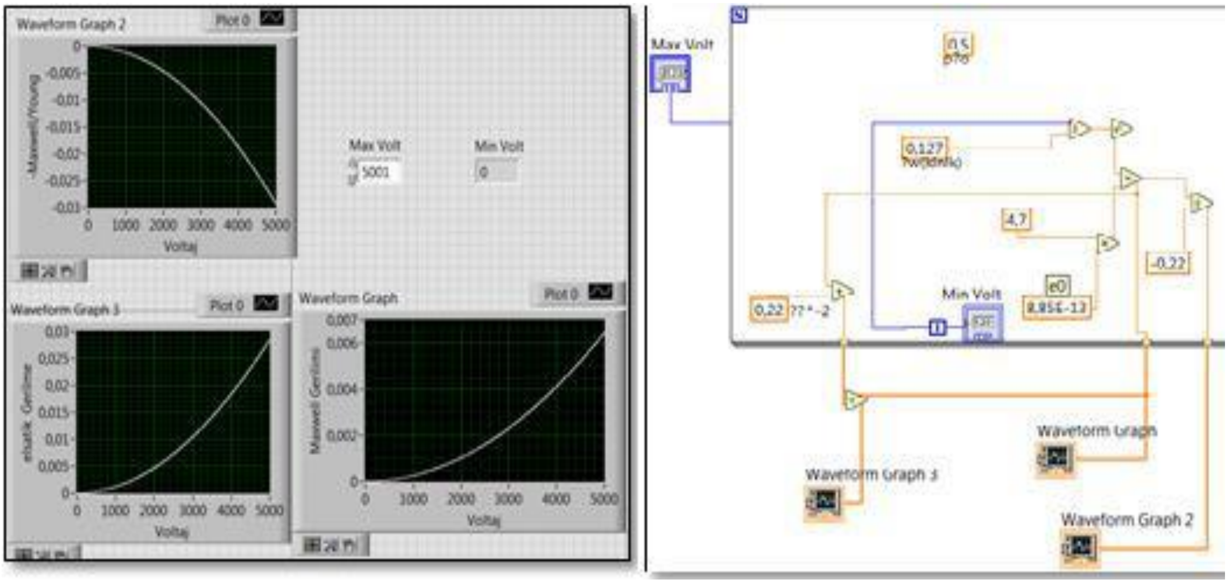


**Figure 4.** Block diagram and representation of the simulations prepared in the Labview program.

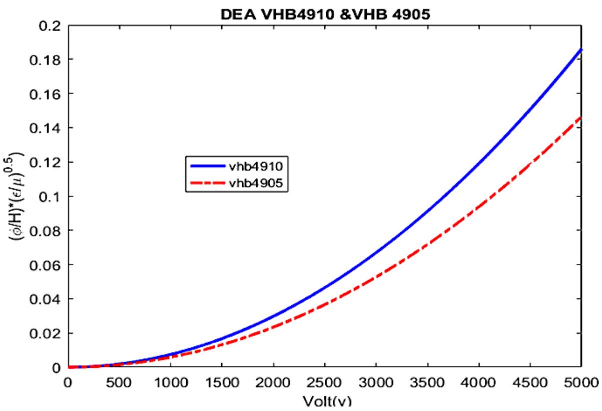


**Figure 5.** Voltage-dependent Maxwell pressure responses of DEAs

In this study, DEAs were examined as the simulation of the reactions of materials close to a living muscle for artificial muscle applications.

As a result of the experiments, in Figure 7, the reaction process was tested when approximately 0 to 5kV was applied in the experimental stage. In this test stage, the EMCO Ap60 DC-DC converter capable of producing 0 to 6kv volts, 3M VHB 4910, and 3M VHB 4905, which are commercially produced bands as dielectric elastomer are used.

In the test process, the dielectric elastomer was pre-streched in certain proportions. Pre-streching is the thinning of the dielectric elastomer membrane. As a result of this process, the reaction of the elastomer whose thickness is thinned when connected to the circuit is calculated in the simulation environment as shown in Figure 8.

The prestressing process is the thinning of the membrane of the dielectric elastomer membrane. When this process is carried out at different rates, the reaction rates are different. For example, the desired reaction is observed by applying less voltage in 75% prestressing than 50% prestressing.

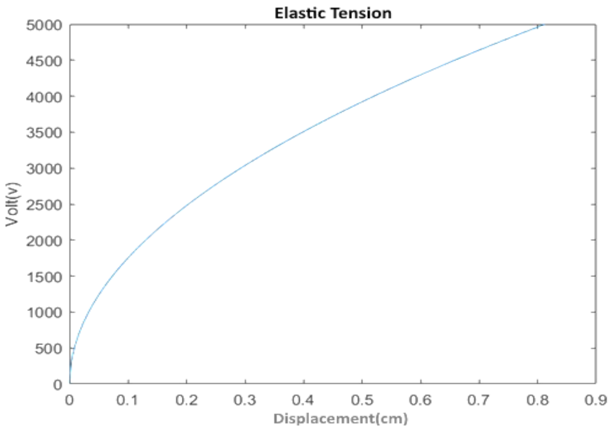


**Figure 6.** Voltage-dependent displacement response of DEAs


**Figure 7.** DEA test results in a) Voltage Off b) Voltage On

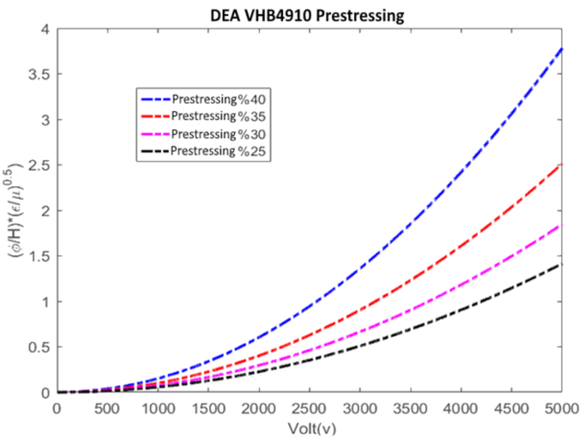


**Figure 8.** Response of DEAs to prestressing.

## 4. Conclusions

Although dielectric elastomers are not exactly analogous to natural muscle, they capture many of the important properties of natural muscles such as stress, tension, strength density, and elasticity. An actuator formed using 3M VHB-4910 or 3M VHB-4905 requires prestressing for faster and more expansion. The most suitable current actuator design for 3M VHB-4910 or 3M VHB-4905 can be considered as a spring actuator. These materials can be used as artificial muscles due to their low power consumption. A dielectric elastomer acts as a capacitor only when the input voltage changes, while still consuming power. At the same time, the leakage current occurring at the DC voltages of the elastomer causes the power consumption to cause high power usage.

Breaking of the dielectric material, short-circuiting due to thin membrane, and applying more voltage than required are reasons that cause damages to the actuator.

The selection of suitable materials, improvements in the production technique, and possible prestressing are important factors that will potentially improve the operating performances of the new actuator. DEAs are having a promising application potential in soft robots.

In this study, experiments and simulations were carried out using VHB4910 and VHB4905 as dielectric elastomers. According to this;

- As the pre-stretching ratio increased, the deformation occurred more.
- VHB4910 deformation occurred more than VHB4905.
- It has been observed in experiments and simulations that deformation increases with increasing stress.
- Deterioration occurred in the dielectric elastomer over 5kV voltage.
- It has been determined that the most suitable voltage range is between 3kV and 5kV.
- According to the results obtained, these results will contribute to the determination of the pre-tension and tension ratio in robotic or surgical applications in a DEA.

One of the most difficult tasks encountered in this application is to supply the DEA with high voltage ranging from 1kV to 10kV. However, the application of this high voltage to DEAs does not pose any safety concerns due to their ability to operate at low currents. In addition, since it works with dc-dc converters, it allows it to be controlled by electronic circuits.

In order to use DEA in surgical and practical applications, it is necessary to know under which conditions the deformation change should be kept.

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**Authors' Contributions**

The authors confirm contribution to the paper as follows: study conception and design: M.Y., İ.K. and D.E.Ş.; data collection: M.Y. and D.E.Ş.; analysis and interpretation of results: M.Y., İ.K.; draft manuscript preparation: İ.K. All authors reviewed the results and approved the final version of the manuscript.

**Competing Interests**

The authors in this publication confirm that they have NO affiliation or affiliation with any organization or organization with any financial interest (such as remuneration; educational grants; participation in speaker offices; membership, employment, consultations, stock ownership). or other equity interest; and expert testimony or patent-licensing arrangements) or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the topics or materials discussed in this paper.

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