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On the Actuation Technologies of Biomedical Microrobot: A Summarized Review

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Abstract

In recent years, wireless microrobots have gotten more attention due to their huge potential in the biomedical field, especially drug delivery. Microrobots have several benefits, including small size, low weight, sensitivity, and flexibility. These characteristics have led to microscale improvements in control systems and power delivery with the development of submillimeter-sized robots. Wireless control of individual mobile microrobots has been achieved using a variety of propulsion systems, and improving the actuation and navigation of microrobots will have a significant impact. On the other hand, actuation tools must be integrated and compatible with the human body to drive these untethered microrobots along predefined paths inside biological environments. This study investigated key microrobot components, including medical applications, actuation systems, control systems, and design schemes. The efficiency of a microrobot is impacted by many factors, including the material, structure, and environment of the microrobot. Furthermore, integrating a hybrid actuation system and multimodal imaging can increase the microrobot's navigation effect, imaging algorithms, and working environment. In addition, taking into account the human body's moving distance, autonomous actuating technology could be used to deliver microrobots precisely and quickly to a specific position using a combination of quick approaches.

Keywords
AMicrorobot, Medical Applications, Actuation Methods, Motion Control, Design Scheme.

I. INTRODUCTION

Over the past few years, there has been a lot of attention in the field of micro- and nanorobots for applications involving efficient medication administration [1]. Microrobots, which are less than a millimeter in size, hold great promise for biomedical applications such as minimally invasive surgery, microassembly, conventional micromanipulation [2], drug delivery, and biosensing [3]. These microrobots, which operate independently, are commonly used for this purpose and are rapidly developing [4]. Moreover, microrobots have been used in another technique for cleaning contaminants inside microchannels has been applied to use them as an alternative due to the small size of the microrobots [5].

Drug delivery is critical for achieving optimal treatment efficacy and also improving drug safety, efficiency, and patient compliance [6]. Modern medication delivery focuses on systems that achieve a balance between treatment tolerance and efficiency [7]. Depending on the location of the tumor and the best management method, precision robots face a variety of long-term challenges [8]. Targeted delivery of drugs could be employed to enhance drug levels in specific cells or tissues while lowering the risk of negative effects elsewhere in the body [9]. Microrobots are considered to be superior drug delivery technologies. They are capable of encapsulating, transporting, and delivering therapeutic contents directly to diseased locations, improving therapeutic efficiency while reducing toxic side effects [10] and reducing pain, recovery time, and cost [7]. Moreover, microrobots are perfect for

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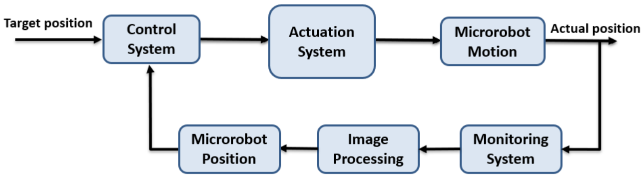

Fig. 1. Block diagram of microrobot system

minimally intrusive tasks due to their ability to enter remote and narrow areas, which could move freely through the blood vessels to their desired location [11, 12]. To be most effective, drug-loaded microrobots must discharge their load in a controlled and timely manner [8]. As a consequence, the limited drug release rate over an extended period prevents the development of microrobot systems for active medication delivery and controlled drug release [13].

Microrobots could be able to accurately access difficult-to-reach or inaccessible parts of the human body [14, 15]. The small force needed for actuation is one of the major features of microscale robotics. Moreover, the ability to use non-contact actuation approaches [16, 17]. These features, represented in the wireless actuation of the microrobots, can be used in different biomedical applications such as targeted therapy, telemetry, hyperthermia, radioactive treatment, scaffolding, stenting, sensing, and marking [18]. Navigating the entire body, including minor arteries, is challenging. Thus, wireless actuation for guided microrobots is a game-changer in intravascular therapies [19]. The most fundamental component of research on microrobots is their scale properties. The study of various aspects of microrobots is based on a thorough investigation of the fundamental theory. Researchers are usually interested in microrobots because of their many uses and potential for microscale exploration. Recently, the research on microrobots has advanced significantly. Fig. 1 shows the microrobot system. All of the above-mentioned features will allow microrobots to make choices in technology for in-vitro tasks involving single-cell placement, cell sorting, cell surgery, and biomedical research.

In this article, we will review the related studies on microrobots. First, a summary of the applications of the microrobots. Second, the main actuation methods of microrobots. Then, control the microrobot's motion and develop strategies. We have divided the various driving methods into four categories: magnetic, optical, acoustic, and hybrid actuation. Finally, the paper is summarized, and the future microrobot characteristics and performance requirements are conceived.

II. ACTUATION METHOD OF A MICROROBOT

The actuation of microrobots has paved the way for many different uses in the last decade, including microfluidics, targeted therapy, drug administration, and microsurgery [20]. Most microrobots are propelled using external electric, magnetic, or light fields, making microrobots out of stimuli-responsive materials that alter their shape in response to changes in environmental conditions [21]. This paper focused on the discussion of external field actuation. The development of microrobots capable of effective propulsion has taken a lot of time and effort. These microrobots may perform self-propelled motions using a variety of propulsion mechanisms [22]. There are different kinds of actuation sources, including chemical, light, acoustic field, and hybrid actuation [23]. The mechanisms of actuation for microrobots are summarized in Fig. 2.

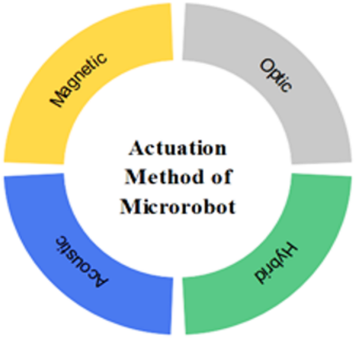

Fig. 2. Mechanisms of actuation for microrobots

Usually, the actuation of microrobots requires the conversion of input energy into mechanical energy. Depending on the type of actuation, it can be classified as physical or chemical actuation. In addition, hybrid actuation provides several actuation options. Hybrid externally applied actuation and self-propulsion are among the modes available [24].

A. *Magnetic Actuation*

Magnetism has attracted a lot of attention in recent years for actuating various types of soft robotics, whether using a system of moveable permanent magnets or electromagnetic coils [25]. Microrobots can be driven by magnetic fields in three different ways: rotating, oscillating, and gradient fields [26]. In general, a wireless microrobot's locomotion is assisted by an external magnetic field [27]. The majority of magnetic microrobots are simple equipment that is driven by external magnetic fields that apply torque and force to the microrobot [28, 29]. Due to the way magnetism functions, magnetic objects tend to move toward areas with strong magnetic fields by moving through the gradient direction of those fields [30]. Applying a magnetic torque, as illustrated in (1), to a magnetized micro/nano object is the fundamental concept of magnetic actuation. An object that is magnetized in a magnetic field suffers a torque (T) that causes the magnetization to line up with the external field [31].

$$T = V.M \times B \tag{1}$$

Where V is the volume of the object, M is the magnetization, and B is the flux density.

Equation (2) describes the force (F) exerted in the presence of a uniform spatial gradient of the magnetic field. The mobility of a magnetic microrobot using these equations is based on the premise that the microrobot may be approximated as a polar and also that non-zero magnetic spatial gradients have a minor effect on the direction and strength of the magnetic field in the microrobot's workspace [32].

$$F = \nabla(M.B) \tag{2}$$

Where ∇ is the gradient operator.

The electromagnetic actuation (EMA) system was capable of creating magnetic fields with various properties, including controllable uniform gradient magnetism, spinning, and an alternating magnetic field [33, 34]. Different types of coils have been suggested by researchers to actuate the microrobot magnetically. A novel EMA system is comprised of stationary and rotational Helmholtz with Maxwell coil pairs. A uniform magnetic flux density is generated by the Helmholtz coils, while a uniform gradient magnet flux is generated by the Maxwell coils [35]. A pair of Helmholtz and Maxwell electric coils make up an EMA system, which is used to fabricate a microrobot [36].

In [37] the authors have proposed a system consisting of three pairs of stationary Helmholtz coils, one pair of stationary Maxwell coils, and one rotating pair of rotating Maxwell coils. The rotating magnetic fields consisted of three pairs of square-shaped Helmholtz coils, which gave the microrobot locomotion and drilling motion. One Maxwell coil pair with a circular shape was developed [38]. A magnetic actuation system that is based on rectangular coils is called RectMag3D. It can control a microrobot in three dimensions with five degrees of freedom of motion [39]. For a smaller volume and less power consumption, an EMA system has been developed using 2-pairs of Helmholtz coils and a pair of Maxwell coils [40]. Helmholtz and Maxwell's coils are also used in an EMA system designed for the microrobot's five degrees of freedom locomotion [41]. The magnetic field created by the source coil is employed for propulsion in wireless power transfer technology, and the Lorentz force is used to generate torque [42].

Another type of coil has been suggested. Two pairs of uniform saddle coils, a pair of Helmholtz coils, a pair of Maxwell coils, and a pair of gradient saddle coils compose the EMA system [27]. For rotating permanent magnets, a novel actuation technology generates less heat while providing the same level of control for untethered microscale objects by using a grid [43]. An untethered magnetic microrobot was activated for navigation using a novel alternating electromagnetic field production technology that was developed and optimized for use with inverted microscopes [44]. Three circular coils placed at the points of an equilateral triangle form a triad of electromagnetic coils that could control a magnetic microrobot's 2D motions within a sizable working area [45]. Fig. 3 illustrates the different shapes of coils. Fig. 3(a) shows the circular type and the structural simplicity of these circular coils. This combination has also been employed by numerous researchers to actuate magnetic robots [46]. Fig. 3(b) shows the square-type, high magnetic field peaks generate at the corners of a square-shaped coil's magnetic field [47]. and Fig. 3(c) shows the saddle type, there have been developments in uniform saddle coils (USCs) and gradient saddle coils (GSCs) [48].

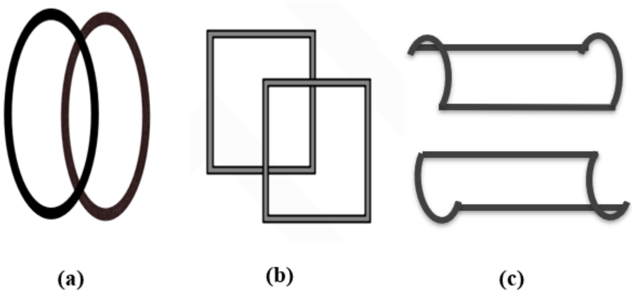

Fig. 3. Different shapes of coils (a) circular coils (b) square coils (c) saddle coils

In comparison with other external actuation methods, the external magnetic field-based control approach has the substantial advantages of wireless connectivity and high efficiency in order to perform motion control of the microrobot at a limited scale. The basic advantages of magnetic actuation include transparency and safety for biological tissues. Microrobots can also wirelessly receive actuation power from an external magnetic manipulation device with a constrained amount of onboard energy storage [23, 29]. Magnetic microrobots have recently started to provide novel prospects in targeted therapeutic administration because of their compact size and capacity to reach challenging locations with minimal surgical intervention [49, 50]. Magnetic fields have the ability to penetrate dense biological tissues, hence magnetic thrust microrobots offer enormous potential for in vivo minimally invasive surgery [51]. Moreover, the magnetic field can reduce chemotherapy's negative risks by lowering drug concentration in other organs [52]. Magnetic soft microrobots have a variety of uses due to their exceptional flexibility, movement diversity, and remote controllability [53]. These advantages have provided very good results for magnetic actuation, which is a

TABLE I.
SUMMARY OF EMA ACTUATION TECHNOLOGIES

Year	Reference	Shape of Microrobot	Number of Coils	Actuation Equipment	Material of Magnet	Speed of Microrobot (mm/s)
2009	[30]	rectangular	5 pair	square	neodymium-iron-boron	8
2009	[40]	cylindrical	3 pair	2 helmholtz and 1Maxwell	neodymium	-
2010	[37]	spherical	5 pair	3 helmholtz and 2 Maxwell	neodymium	-
2010	[32]	elliptical	8 coils	cylindrical octomag	neodymium-iron-boron	-
2010	[35]	cylinder	2 pairs	2 helmholtz and 2 Maxwell	neodymium	0.5
2011	[38]	spiral	4 pair	3 helmholtz and 1 Maxwell	neodymium	-
2014	[29]	cylinder	8 coils	cylinder	-	-
2015	[50]	hybrid	3 pair	3helmholtz	neodymium	4.74
2017	[27]	spiral	5 pairs	1 helmholtz, 1 Maxwell and 3 saddle	-	-
2019	[34]	capsule	5 pairs	1 helmholtz, 1 Maxwell, 3 saddle	neodymium	-
2020	[39]	cone	8 coils	rectangular octomag	neodymium-iron-boron	-
2020	[12]	spherical	8 coils	circular coils	neodymium-iron-boron	-
2020	[45]	disk	3 coils	identical circular coils	neodymium	2.5

promising actuation approach for biomedical applications. Every magnetic device or object will interact with the magnetic field. The frequency, magnitude, and direction of the magnetic field can be varied to allow different robots to modify their posture, speed, and direction. It is possible to consider the multi-degree of freedom of a robot due to the fact that robots with varied structures will react to the magnetic field very differently. Table I shows the summary of EMA actuation technologies with different numbers, and shapes of coils.

B. Optic Actuation

A microrobot that has used optical micromanipulation technology is known as an optical microrobot [54]. The direction, polarization, wavelength, and intensity of the incident light may all be accurately controlled through the use of light actuation, which is also exhibiting great promise as a method of propulsion [55]. A novel micro-rocket robot has been developed that includes an all-optic drive and an imaging system that can precisely actuate and monitor it at the microscale [56]. Also, phototaxis was used to develop a mechanism for steering swimming cells. The approach used a changing light signal, and their motions along set trajectories were effectively accomplished under optical control [57]. The ability to control mobile micro devices with light has several inherent limitations. Light-based systems are mostly restricted to two-dimensional control, whereas magnetic and acoustic fields can control micro-objects in three dimensions. The workspace must also be optically accessible for control, and the micro devices must move in a clear, transparent medium. Therefore, medicinal applications in bodily tissues are very challenging. Fig. 4 shows the optic actuation of the microrobot.

C. Acoustic Actuation

Another attractive and practical method for wirelessly activating and functionalizing microrobots is acoustic actuation. Acoustic vibration fields have been used to generate vibra-

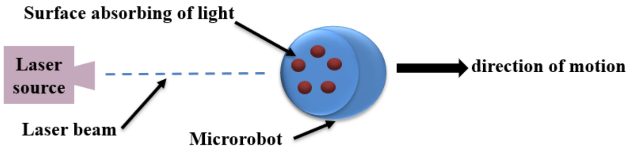

Fig. 4. Optic actuation of the microrobot

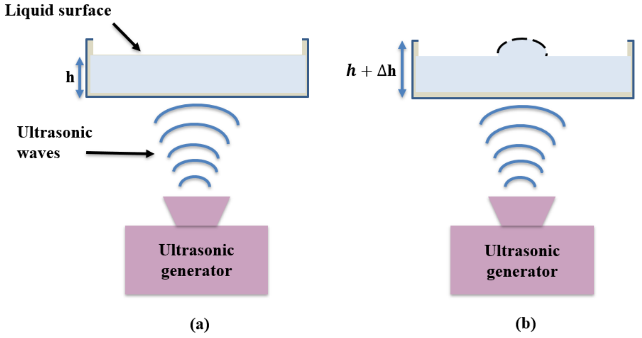

Fig. 5. Concept of acoustic actuation (a) before actuation (b) after actuation

tions and thus the movement of microrobots. In actuality, acoustic fields are commonly used in two main ways: standing waves and traveling waves [58]. Ultrasound is a relatively new method that has been applied to drive micro and nanorobots [59]. Acoustic field actuation was dependent on sound waves that radiated from the microrobot. The sound propagation direction is the same as the movement direction. Examples of sound waves include surface sound, pulsed ultrasound, ultrasonic standing waves, and ultrasonic [60, 61]. Acoustic field actuation has several benefits including great tissue permeation, biocompatibility, and high flexibility [59]. Acoustic levitation appears to be the best option for micro-assembly in most cases. Acoustic actuation is a biocompatible kind of actuation that can be utilized in combination with magnetic fields to increase the swimmers' propulsion and steering [62]. The energy of an ultrasonic beam is attenuated as it passes through tissue due to absorption and scattering. Heating occurs as a result of tissue energy absorption [63, 64]. The main benefit of acoustic processing is that it can manipulate any material by acoustic forces. When given enough sound power, a stable equilibrium position always exists. Surface features, such as roughness, were influenced by fluid movement and the acoustic field. Acoustic stream and force field non-uniformity are the main disadvantages of acoustic levitation [65]. Fig. 5 illustrates the concept of acoustic actuation of the microrobot. The acoustic field's vibrations, which are the basis for bubble propulsion, are strong when acoustic frequencies reach the bubble's resonance frequency. Fig. 5(a) shows the inactivity of the liquid surface by ultrasonic waves before acoustic actuation, due to the acoustic field's insufficient selectivity to the object being manipulated and Fig. 5(b) shows the effect of the liquid surface after directing ultrasounic waves towards it after acoustic actuation, when the sound field's frequency and the bubble's resonance frequency are equal, the bubble vibrate effectively.

D. Hybrid Actuation

The benefits of several actuation techniques can be combined through hybrid actuation, which can also enhance the performance and functionality of microrobots in complex environments [66]. The most commonly used actuation techniques in micro-robotics are magnetic and optical. They can both be used to actuate a set of microrobots quickly, precisely, and over a longer distance. Microrobots with magnetic actuation may penetrate nontransparent tissues at great depths for medical applications, but microrobots with optical actuation are better suited for biotechnology [67].

The potential for combining the benefits of both approaches in new robot designs is very important. Although synthetic micro/nanomotors are effective at delivering medications, using them inside the human body presents a number of challenges. Due to their improved biocompatibility, biodegradability, and functional connections with physiological tissue, biological hybrid systems have recently become an alternative [68]. Target medication delivery techniques use electromagnetic actuation to move the microrobot and acoustic bubble actuation to manipulate the drug [36]. A microrobot in the shape of a bullet is equipped with an air bubble that is acoustically trapped inside its internal body cavity. Due to the net fluidic flow brought on by the bubble oscillation, the microrobot is driven laterally at extremely high speeds while also creating an attractive force toward the wall. The direction of the microrobots' movements is controlled by directing them into a uniform magnetic field [69].

III. MOTION CONTROL OF MICROROBOT

The primary goal of the control scheme is to get the microrobot to the desired position using the Manipulation Control Algorithm. In addition, any actuation method needs auxiliary actuation, control, and imaging equipment to drive and control mobile microrobots remotely [70, 71]. Planning robot trajectories is a challenging task that is essential and plays a crucial role in the design process [72]. Therefore, the development of model-based control algorithms requires a robust microrobot motion model. The movement of these small robots is affected by surface tension, friction, and viscous forces, which make it difficult to obtain a good estimate of these forces [73]. At low fluid flow velocities, the drag force was less significant than the friction force. The friction force contributed a lot to microrobot control and drag force measurements [74]. Cylindrical microrobots have the same diameter but different lengths. The frontal area and not the length were the only variables influencing the drag forces [75].

A closed-loop control technique based on location information feedback was developed [41, 76]. Time-delay estimation (TDE) is used to model and implement a closed-loop control scheme for a magnet-actuated microrobot [29]. In the

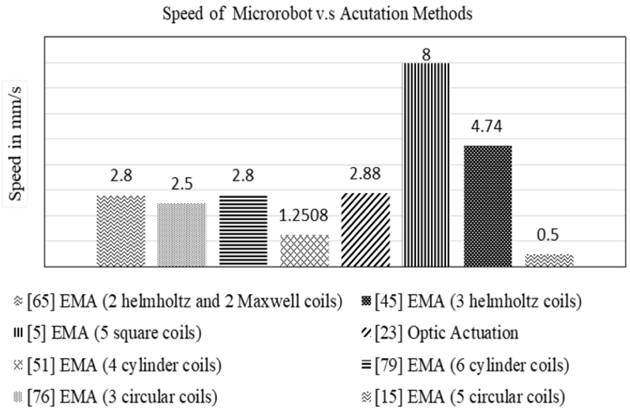

Fig. 6. The speed of microrobots in different actuation systems

lower-viscosity fluid, the controller performed better. In comparison to the PID controller, the TDE controller responded faster and less clatter [77]. Using an infrared light-emitting diode, a wireless remote controller transmits signals. An optical receiver module positioned on the microrobot's body receives the transmission signals [78]. With an optimized control scheme with optical coherence tomography imaging feedback, the optimal PID output was designed [79].

For microscale applications, the microrobot's speed is essential. For evaluating the performance of the microrobot, maximum speeds can be examined [80]. In this review, the microrobots' maximum speeds were obtained to analyze their performance. The speed of a microrobot has different values in each system depending on many factors, such as actuation method, number of coils, size, and shape of the microrobot, and application environment, Fig. 6 shows that the shape of coils has a significant association with the microrobots' maximum speed at the same number of coils but different in shape will get the different value of the speed.

IV. DESIGN SCHEMES OF MICROROBOT

The reliable, safe, and accurate application of microrobots requires control and communication with the operator. Moreover, a microrobot's design must be compatible with the specific medical application scenario [81, 82]. Biocompatibility and biodegradability materials should be addressed in the microrobot for clinical usage, and its efficacy must be evaluated using an in vivo model [83, 84]. Microrobot modeling and design depend on the operational conditions and tasks that are required to be executed [7]. On the other hand, the hexahedral microrobot had a greater surface area and volume than the cylindrical microrobot. It moves more slowly due to a greater resistive force [85]. The magnetic flux density and the number of spirals in the microrobot affect its movement. Two different kinds of magnetic spiral microrobots were examined, with different numbers of spirals (5 and 10, respectively). The maximum speed at 15 Hz is 11.8 mm/s for ten spiral numbers in the horizontal direction and 3.64 mm/s for five spiral numbers in the vertical direction [86]. The results of experiments indicate that speed rises when magnetic flux density and spiral number increase. In particular, at high rotation speeds, the performance of the microrobot with ten spiral numbers is better than the microrobot with five spiral numbers.

As a result, the cylindrical microrobot design is advantageous for reducing the resistance to manipulation. There are various shapes for the design of the microrobot such as cylindrical [29], helical [13], and rocket [56]. In general, Helmholtz coils that are circular or square are employed to create a uniform magnetic field. Therefore, it is essential to examine the method the Helmholtz coil's shape performs. Designing two different types of Helmholtz coils, square and circular, both with the same electric current parameters. The magnetic flux density gradually increases from 0.4 to 1 m [87]. As a result, the circular Helmholtz coil produces a greater magnetic flux density than the square Helmholtz coil. The designing and controlling of the microrobot must be taken into account depending on the task they will be accomplishing and the type of operating environment. However, the speed of the microrobot is highly dependent on its shape and size.

V. CONCLUSION

In this paper, we have reviewed summaries on the biomedical application, the actuation process, design, and motion control of microrobots. According to related work, magnetism is a promising method for steering magnetic microparticles from their application location to cancer because external long-range magnetic fields could reach cancer everywhere in the body. On the other hand, recent and previous experimental results indicated that the performance of microrobots is affected by several factors, including the size of the microrobot and its location in the body, as well as the composition and architecture of the tissue or fluid in which the microrobots operate. The researchers established that the magnetically actuated microrobot was able to achieve simple forward and backward movements. Meanwhile, by adjusting the magnetic field's strength and direction. The structure of the coil, the material properties, and the design parameters of the actual coils are further optimized will cause the microrobot's speed of movement has been modified.

The development of modular tracking and controlling systems for microrobots in real-time is one of the challenges that must be overcome. By comparison, the TDE controller performed better than the PID controller. The TDE controller responded faster and more accurately. In addition, the microrobot, which has a greater surface area and volume, moves more slowly due to a greater resistive force. As a result, the smaller size of the microrobot in design can reduce the resistance to manipulation and increase the velocity.

Future research on the actuation of the microrobots should therefore concentrate initially on the actuation of 3D space. Secondly, to give accurate control of the mobility of microrobots inside the body, reliable movement and steering control must be applied in constrained environments like cancer monitoring and treatment. Thirdly, whole-body work can be achieved by hybrid actuation, which combines fine and long-range actuation. Lastly, to overcome the constraints of a single microrobot in the body, actuation, and control of microrobot populations are urgently required For microrobots to be utilized as standardized tools in biomedical applications, however, biodegradability and biocompatibility require being further developed and investigation on a larger scale.

CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

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