Development the flexible magnetic abrasive finishing process by transmitting the magnetic fields

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Received: 26 January 2021 / Accepted: 23 October 2021 / Published online: 2 December 2021 © The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2021

Abstract
This research aims to present a novel approach in magnetic abrasive finishing to improve its potential for creating different finishing patterns in the free-form surface using no special fixtures or tool machines to minimize the complexity of the process. The key point of this idea is that magnetic abrasive particles can move in special patterns by transfer magnetic fields (similar to a magnetic train moving on a magnetic rail) and create the desired polishing patterns on the surface simultaneously. The coils are placed under a thin plate; then, a flexible magnetic path is created by a special arrangement of magnetic coils; after that, the coils are turned on and off in turn, and the magnetic abrasive particles move in the created path and abrasive the surface. The continuous movement of magnetic abrasive particles under the magnetic field will abrade the thin sheets’ surface. The tests were performed on copper sheets with a thickness of 1 mm. Experimental parameters include electric current (0.25, 0.5, and 0.75 A), speed of turning on and off of the coils (speed of magnetic abrasive particle movement) (20, 30, and 40 mm/s), and process time (1, 2, and 3 h). The experiments were performed on L-shaped and free-form sheets. The results show that using a transmission magnetic field in the MAF (TMAF) makes it easy to create different surface roughness patterns in different directions simultaneously. While in one part of the L-shape the electric current is 0.25 A, the surface roughness is around 0.90 µm, in the other part, where the electric current is 0.75 A, the surface roughness is around 0.49 µm. Meanwhile, TMAF makes it possible to finish a free-form surface with no special fixtures. Moreover, there is a direct relationship between the change in the surface roughness and the electric current and process time.

Keywords Magnetic abrasive finishing · Surface roughness · Magnetic field · Abrasive particles · Magnetic coil

1 Introduction
The magnetic abrasive finishing (MAF) process was introduced by American and Russian researchers [1]. The MAF process is one of the significant non-traditional metal finishing processes by employing magnetic fields and magnetic abrasive particles [2]. In the MAF process, a magnetic field is used to force abrasive particles against the target surface; furthermore, these magnetic abrasive particles can move on the surface of the workpiece while the magnetic field bonds them to the surface. In the MAF technique, cutting tools consist of iron and abrasive particles [3].

To apply the MAF technique, a machine tool, abrasive particles, medium composition, and process settings are essential. In many types of research, conventional production machines such as lathe and milling have been utilized for the MAF process according to the workpiece geometries [4]. In the case of MAF for cylindrical surfaces, a lathe can typically be used. Cylindrical parts are typically chucked in a small lathe [5]. In the case of MAF for flat surface, by using milling machines, the magnetic tool is chucked in the spindle and rotated which the magnets are placed a few millimeters above the parts [6]. Meanwhile, a number of researchers introduce special MAF machines to finish complex workpieces by developing free-curved tools which are inserted into the spindle or using robot arms [7]. While few researches utilize permanent magnets [8], others prefer to use electromagnetic inductor which consists of an inductor of steel road wrapped with a coil of wire [9].

The MAF has unique potential in some applications such as finishing the inner of tubes and free-form surfaces as well
as eliminating the side effects of other finishing processes. One of the main applications of the MAF technique is to finish the inner of the tubes. The inner roughness of tubes has a significant effect on the system performance; however, improving their surface roughness is difficult using the conventional finishing method. Meanwhile, the MAF system can be used to produce good surface quality efficiently [10].

Wang and Hu described the principle of the process and finishing characteristics of unbounded magnetic abrasive to finishing the internal of a tube. Wang studies the effect of internal magnetic abrasive finishing of thin and long austenitic stainless steel tubes [11]; in addition, improving the internal surface finishing of the bent tube made of stainless nitic stainless steel tubes [11]; in addition, improving the internal magnetic abrasive finishing of thin and long austenitic stainless steel tubes [11].

In the current research, a new MAF technique is developed to increase the flexibility of this technique. The key point of this idea is that bound magnetic abrasive particles (sintering or other processes) follow the transmitting of magnetic fields (similar to a magnetic train moving on a magnetic rail). The principle of this technique (Fig. 1) is that the magnetic field, which is produced by electromagnetic coils, transmits from one to another coil, which is placed in a special arrangement under a thin sheet. Firstly, the coils are prepared and then mounted on the insulating surface in several rows and below the workpiece. An electrical circuit turns on or off coils according to the finishing pattern (the current of each coil is controlled individually). It is not necessary to change the physical pattern of coils so that using them is not time-consuming. Subsequently, the magnetic field flows in a special path (based on coils arrangement) by turning on and off the coils controlled by an electronic circuit. Afterward, the magnetic force (produced by special coils arrangement) determines the path of the abrasive particle movement and finishes the surface of workpieces.

The magnetic field is created by a coil in which an electrical current flow in the wire around the core as shown in Fig. 2; several electromagnet coils are placed next to each other. They can be arranged in many different forms based on the geometry of workpieces or desired special patterns. Electrical current flows to the electromagnetic coils in turn; thus, it creates a magnetic field in each coil. An electrical circuit controls the electrical flow and turns on or off the coils in turn; therefore, the generated magnetic field is transmitted from one coil to another (each coil becomes a magnet in turn) and creates a flow of magnetic fields. The magnetic fields which are generated and transmitted by coils bound the abrasive particles on the surface and move them in special directions. Due to the special arrangement of electromagnetic coils, transmitting a magnetic field from one coil to another creates a special path that makes magnetic abrasive particles move based on special patterns created by electromagnetic coils arrangements. The schematic of the process is shown in Fig. 3. The experimental finishing setup, the workpieces, and the movement of magnetic abrasive particles under the magnetic force generated by the coils are shown in Fig. 4. The abrasive particles can be moved in the x, y, and/or z directions concerning the magnetic field. The
movement of the abrasive particles concerning the arrangement of magnet coils can reduce the surface roughness ($Ra$) of the workpiece and creates special patterns on the surface of the workpiece.

### 2 Materials and equipment

The main elements of TMAF equipment include the electromagnet, magnetic abrasive particles, and electronic circuits.
Several electromagnetic coils are designed and manufactured to implement magnetic force on the workpiece. A magnetic core, made of permalloy, is used to confine and guide magnetic fields. To boost the efficiency of the magnetic field and decrease the heat-producing by coil during the process, the cores consist of lamination plates. In this study, the thickness of each plate is 1 mm and there are 10 plates in each core; moreover, the cores are designed in the form of I and the wire diameter is 0.5 mm as shown in Fig. 2. Each coil has around 2000 turns (200 turns per centimeter). Meanwhile, the magnetic field strength of the coils is measured using a magnetometer (Model MG-3002). An electronic circuit is designed to turn off and on the electrical current on the coils in turn. The designed electronic circuit has the potential to change the speed of turning coils off and on. The coils are glued on an opposite side of the plate to arrange the coils for creating finishing L-shape and free-form patterns (there is no distance between coils and plate surface).

### 2.1 Electromagnet setup

As abrasive particles such as aluminum oxide are non-magnetic materials, and the magnetic field does not act on the abrasive particles. So bound magnetic abrasive particles (sintering) are used for the abrasive process. The sintered magnetic abrasive technique is employed to prepare abrasive particles based on [18] by mixing iron powder (45 µm size, 60% by weight) and alumina powder (5 µm size).

![Image of magnetic force applied on magnetic abrasive particles](image-url)

**Fig. 3** The schematic of magnetic force applied on magnetic abrasive particles (coil no. 1 is turned on and exerts a vertical magnetic force on the abrasive particles, then coil no. 1 is turned off and coil no. 2 is turned on, causing a horizontal force (sliding force) to be applied to the abrasive magnetic particles. And the result of the forces will lead to the movement of magnetic abrasive particles and eventually surface wear.

### 2.2 Magnetic abrasive particles

![Image of experimental setup](image-url)

**Fig. 4** Experimental setup (movement of magnetic abrasive particles under the magnetic force generated by the coils. Magnetic abrasive particles move at the surface of the copper plate).
size, 30% by weight) with polyvinyl acetate (PVA), which is used as the bonding agent (10% by weight) [18]. The magnetic abrasive particles include the alumina shell along with the iron particle, which is employed as the magnetic core of individual abrasive particles (Fig. 5). Meanwhile, grinding fluid is not used in the experiment.

2.3 Workpiece materials

The plates made of copper with the thickness of 1 mm are used for the experiments as the workpieces. Meanwhile, a free-form plate is used having the same thickness.

2.4 Surface roughness measuring

After each experiment, the change in surface roughness value (Ra) is determined by Surface Roughness Tester TIME3202 (the model of TR220) with the resolution of 0.01 µm. The initial surface roughness (Ra) of the samples is varied and is nearly 2 µm. The morphology of the surface has been studied using atomic force microscopy (AFM) model MFLI with a resolution of 0.12 nm. The measuring direction of surface roughness is perpendicular to the direction of movement. Meanwhile, the surface roughness is measured in the center of the coil (length 1 mm) (equal to the amount of propeller movement of the roughness tester) as shown in Fig. 6. Meanwhile, NMR20 Gaussmeter is employed to measure the magnetic field intensity at the middle of coils.

2.5 Experimental settings

The three effective parameters have been taken to conduct the experiment on the TMAF as shown in Table 1. It should be mentioned that the TMAF is applied in two manners: first, for flat surfaces enabling two paths (directions) to be finished simultaneously (L-shape) and second, for free-form surfaces (all tests repeated five times).

3 Results and discussions

The experimental results show that the surface morphology of the plates has changed significantly after the TMAF process. Atomic force microscope (AFM) images) Figs. 7 and 8) confirm that the surface morphology has improved after the TMAF process. Figure 7 shows that the surface morphology is improved by increasing process time. Furthermore, Fig. 8 also shows that with increasing electrical current in the coils, the surface morphology is improved, and the surface roughness is reduced (the height of peaks and valleys is reduced).

The reason for the improvement of the surface morphology can be related to the magnetic force applied to the magnetic abrasive particles (the electric current in the coils creates a magnetic field, which leads to applying the magnetic force on magnetic abrasive particles) as shown in Fig. 3. The magnetic field strength at the center of a coil is [19]:

Table 1 The experimental parameters

| Process parameter                      | Level 1 | Level 2 | Level 3 |
|----------------------------------------|---------|---------|---------|
| Finishing time (hours)                 | 1       | 2       | 3       |
| Abrasive particles speed (mm/s)*       | 20      | 30      | 40      |
| The electrical current (A)             | 0.25    | 0.5     | 0.75    |

*The average speed of abrasive particles is measured by measuring the time between off and on coils and the distance between the centers of two coils.
where $N$ is the number of turns of the coil, $L$ and $I$ are the length and the current in the coil respectively, $k$ is the relative permeability of the core, and $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic permeability.

The magnetic force is proportional to the gradient of the magnetic field. The magnetic force $F_V$ can be calculated from the equation [20]:

$$F_V = \mu_0 V(M \cdot \nabla)H$$  \hspace{1cm} (2)

The magnetic polishing pressure $P$ can be considered as [21]:

$$P = \frac{B^2}{2\mu_0}(1 - \frac{1}{\mu_r})$$ \hspace{1cm} (3)

where $\mu_r$ is the relative permeability of magnetic abrasive particles.

Also, the normal component of the magnetic force can be considered as [22]:

$$F = PA$$ \hspace{1cm} (4)

where $A$ is the contact area of the magnetic abrasive particle with the workpiece surface.

The magnetic field applies pressure on the surface of magnetic particles. The magnetic field applies a vertical force to the magnetic abrasive particles on the surface plate. Then, applying the forced leads penetrates magnetic abrasive particles onto a surface; eventually, the movement of thousands of particles leads to the cutting and shaving of the surface peaks. Based on Eq. 1, increasing the current will increase the intensity of the magnetic field. Measurements with a magnetometer show that the intensity of the magnetic field with an electric current of 0.25 A is 0.124 T, and with increasing current intensity to 0.5 and 0.75 A, the intensity of the magnetic field increases to 0.131 T and 0.181 T, respectively. Therefore, as the electric current in the coil increases, the intensity of the magnetic field increases, and as a result, the magnetic force exerted on the abrasive particles will be enhanced (based on Eq. 2). Based on Eq. 3, rising the magnetic field intensity leads to increasing the polishing pressure and the normal magnetic force of magnetic (based on Eq. 4) brush acting on the workpiece. As a result, with the increase of the magnetic field, it can be expected that the polishing pressure will increase and more force will be applied to the magnetic abrasive particles, and the surface roughness will improve (Fig. 8). Also, increasing the TMAF processing time leads to more abrasive particles in contact with the surface and more scratches on the surface peaks and improves the surface morphology (Fig. 7).

3.1 Creating similar surface roughness in the two directions simultaneously by the TMAF

Having the goal of polishing two perpendicular directions (L pattern) simultaneously (two paths that are perpendicular), magnetic coils are arranged in two perpendicular directions which create an L pattern (by the arrangement of coils) as shown in Fig. 9. Therefore, magnetic fields propagate to electromagnetics in turn and the mixture of magnetic abrasive particles moves along the surface of the workpiece in response to the magnetic field (L pattern) and improves the roughness of the surface in harmony with having L pattern. Although the experimental conditions are the same in both paths, the purpose of this experiment is to show that abrasive particles can move in an indirect path (L-shaped path) and wear an asymmetric surface in a process.

The measurements show that the surface roughness ($Ra$) in two directions (path A-B and path B-C) is the same for different process parameters as shown in Figs. 10, 11, and 12. In the case of 0.25 A (finishing time is 1 h and particle speed is 20 mm/s) (Fig. 10), surface roughness is around 0.90 µm in both paths of A-B and B-C. In addition, in the case of 0.5 A (finishing time is 1 h and particle speed is 20 mm/s), surface roughness is roughly the same, 0.76 µm, in both paths of A-B and B-C. Also increasing the electrical current to 0.75 A leads to improving surface roughness to around 0.49 µm which is similar in both paths. There is a same trend in Figs. 11 and 12 for different process times and

![Fig. 7 Atomic force microscopy (AFM) images, A initial surface, B after 3 h TMAF process (electrical current is 0.5 A, particle speed is 30 mm/s for all cases)](image)

![Fig. 8 Atomic force microscopy (AFM) images, A initial surface, B electrical current is 0.75 A in coils during TMAF process (time of the process is 2 h, particle speed is 30 mm/s for all cases)](image)
magnetic particle speeds. It is evident from the figures that transmitting magnetic fields have the same effect on the two directions. This could be due to the magnetic force exerted on the magnetic abrasive particles. Although magnetic abrasive particles move in two perpendicular paths (paths of A-B and B-C), due to the arrangement of the coils, the magnetic field strength of the two paths is similar (because the electric current in the coils is the same in both paths, so the magnetic field strength of the two paths is the same). Therefore, the magnetic force exerted on the magnetic abrasive particles is also constant along both paths, and as a result, the surface roughness is the same in both paths. This strategy (same current in coils of paths) makes it possible to create surface roughness in various paths without the use of special tools or fixtures and even robot arms. And it is technically feasible to abrade different paths with the same quality just by arranging different coils, which can reduce the cost of the machining process and make it more flexible. Also, as shown in Figs. 10, 11, and 12, by selecting the test parameters, the desired surface roughness can be created.

3.2 Texturing with the TMAF

Creating different surface roughness is vital for some applications; thus, the magnetic force for the bound abrasive particles to the surface should be different. As the current of each coil can be controlled individually, it is possible to create a different magnetic field in each coil. It assists to press magnetic particles to the surface having different magnetic forces. In Fig. 13, in the case of selecting 20 mm/s for speed of particles and 1 h for process time, the surface roughness is around 0.76 µm and 0.65 µm for the electrical current of 0.25 A (in the path of A-B) and 0.5 A (in the path of B-C). There is a similar trend in other different speeds of particles as
shown in Figs. 13 and 14. In fact, we generate different magnetic forces in the two preopercular paths (path A-B and path B-C) by increasing the electrical current in the coils located in the path B-C compared with the path A-B ones (electrical current in coils located in path B-C is more than path A-B ones). As a result, the magnetic field strength in path B-C is higher than that in the path A-B. As expected, the surface roughness in the path B-C with a higher magnetic field is lower than that in the path A-B. As mentioned earlier, this is due to the magnetic force exerted on the magnetic abrasive particles. As the abrasive particles are magnets, the magnetic field strength and the force exerted on the abrasive particles are proportional to the electric current of the coil (based on Eqs. 1 and 4). In a particular path (path B-C), an increase in the electric current of the coils leads to an increase in the magnetic field, and increasing the magnetic field leads to increasing the magnetic force applying on the magnetic abrasive particles and ultimately improving the surface roughness. Therefore, by changing the current intensity in the coils in different paths, different surface roughness can be created.

Meanwhile, it is clear from Figs. 13 and 14 that increasing the speed of magnetic abrasive particles decreases the surface roughness. While, in the case of 0.5 A for electrical current (Fig. 13), the surface roughness is around 0.65 µm, it decreases to around 0.48 µm when the speed of particles rises from 20 to 40 mm/s. The empirical equation of Preston explains the effect of speed of particles and pressure on the rate of material removal from the surface in the polishing process [23]:

\[ M = kPS \]  

\( P \) is the pressure or force per unit area, \( S \) is the speed of the abrasive particles relative to the surface, and \( M \) is the rate of material removed (cutting depth per unit time). The constant, \( k \), is known as the Preston coefficient.

The formula basically states that the rate of removal of material during grinding and polishing is proportional to the pressure times the speed of abrasive particles. Based on the simple equation of Preston, the rate of surface removal rises as the downward force (magnetic force) on the workpieces increases or if the speed of the abrasive particles increases. Obviously, \( Ra \) reduces by increasing the electrical current, particle speed, and finishing time. Increasing the speed of abrasive particles and process time causes more abrasive particles in contact with the surface, which ultimately leads to improved surface smoothness. It can be seen from the results that the improvement in surface roughness increases by enhancing the speed of higher magnetic particle movement. Material removal is essential for improving the surface roughness. The rate of material removal depends on the relative motion between the magnetic abrasive particles and the workpiece. The faster motion of magnetic particles leads to reduction in surface roughness. The improvement in surface roughness can be due to more abrasive particles that come in contact with the workpiece during high speed because of more cutting edges of magnetic particles available per unit of time, which removes the micro and nano hills and valleys effectively to give greater change in surface roughness. At the same time, the number of cutting edges increases by increasing the speed of particles. At the higher speed of particles, the horizontal force is also large and the chances of abrasive particles to indent into the workpiece surface and breakdown the micro hills of the surface increased. This may result in a reduction in percentage change in surface roughness. However, it should be mentioned that rising the speed of abrasive particles (more than 50 mm/s) is also

![Fig. 13](image1)  
**Fig. 13** The effect of TMAF on the surface roughness in two perpendicular directions with different magnetic fields’ value (electrical current of coils in path A-B is 0.25 A, and electrical current of coils in path B-C is 0.5 A) (finishing time is 1 h) (error bars represent standard deviation of five independent experiments)

![Fig. 14](image2)  
**Fig. 14** The effect of TMAF on the surface roughness in two perpendicular directions with different magnetic fields’ value (electrical current of coils in path A-B is 0.25 A, and electrical current of coils in path B-C is 0.75 A) (finishing time is 1 h) (error bars represent standard deviation of five independent experiments)
limited, because abrasive magnetic particles cannot follow the motion of the magnetic field at high speed.

### 3.3 Finishing of free-form surface by the TMAF

Having the aim of improving the surface roughness of the free-form surface, the magnetic coil configurations are adopted using the surface curves as shown in Fig. 15 (all coils are in parallel). The surface roughness ($R_a$) of a free-form surface and a flat plate made of copper are compared as shown in Table 2. In the case of employing 0.25 A and 1 h, the surface roughness is $0.96 \pm 0.1 \, \mu m$ and $0.959 \pm 0.9 \, \mu m$ in curve and flat surface, respectively. As shown in Table 2, variation in process parameters results in a change in the surface roughness. As expected, the proposed TMAF technique enables us to reduce the roughness of the free-form surface as the same as the flat plate. However, since the parameters in the free and flat specimens are the same, so the surface roughness change is the same. As a result, this technique has a unique potential for improving the roughness of free-form surfaces, just by arranging electrical coils, instead of using a robot or special fixture to finish the curved plates.

The three-dimensional simulation of the magnetic field strength distribution in the processing area and the value of the magnetic field strength is shown in Fig. 16. It is clear that the distribution of the magnetic field in the coil is not uniform. In addition, the value of the magnetic field around the center of the coil is also different. As can be expected, the three-dimensional simulation shows that the intensity of the magnetic field decreases with decreasing electric current, and this is one of the major challenges of this technique that should be considered and improved in the future.

This technique improves the performance of the MAF when the different surface patterns for complex-shaped metal parts are desired. In other words, drafting different surface patterning and smoothing in different directions simultaneously is the ability of this method. Besides, it is clear that conventional machine tools are not required and vibrations in the machining center and machining tool are not transmitted onto the workpiece surface; thus, it can efficiently finish ceramics, carbides, coated carbides, and silicon. Moreover, all functions can be controlled by electric and electronic units which make the MAF process more appropriate for automation production lines. Evidently, automating the finishing process leads to reducing production costs while ensuring quality control. Meanwhile, it can be deduced from the results that $R_a$ reduces with increased three factors of the inductor current, particle speed, and finishing time. Electrical current is found to be a significant

| Table 2: The effect of TMAF parameters on the surface roughness in flat and curve surface |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Current (ampere) | Machining time (hours) | Speed of machining (mm/s) | $R_a$ (µm)* | Flat surface | Curve surface |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.25 | 1 | 10 | 0.96 ± 0.1 | 0.959 ± 0.9 |
| 0.25 | 2 | 15 | 0.77 ± 0.0 | 0.775 ± 0.2 |
| 0.25 | 3 | 20 | 0.58 ± 0.2 | 0.595 ± 0.0 |
| 0.5 | 1 | 10 | 0.81 ± 0.0 | 0.810 ± 0.2 |
| 0.5 | 2 | 15 | 0.62 ± 0.1 | 0.625 ± 0.1 |
| 0.5 | 3 | 20 | 0.42 ± 0.9 | 0.43 ± 0.0 |

*Values represents the mean ± SD of all tests (the number of measurements is 5)
parameter. It is clear from the results that an increase in magnetic flux density leads to reducing in surface roughness. The current input to the coils of the electromagnet generates the magnetic field, which controls the magnetic force that bonds the magnetic particles on the workpiece. In other words, the magnetic flux density dictates the finishing force that is governed by the electrical current in coils. When electrical current values grow up, the vertical normal force is dominant and increases indentation of abrasive in workpiece surface and causes an increase in percentage change in surface roughness. Therefore, shifting the electrical current from low level to high level leads to enhancing the magnetic flux density in coils.

3.4 Limitations of TMAF

Despite the benefits of this method, during the tests, some of the limitations were observed. This method can only be used for non-ferrous plates. Iron plates will be magnetized entirely by electromagnetic coils; therefore, magnetic abrasive particles will not move on the iron. Coil size is also another limiting factor. By reducing the size of coils, the magnetic force also decreases. Since the magnetic field strength decreases rapidly as the distance increases, this method can only be applied to thin plates and cannot be used for bulk objects because the gap between the coil and the abrasive particles must be small enough that magnetic force can be applied to it and direct them. But in bulk objects, by increasing the distance (between coils and the magnetic particles on the surface), the magnetic force diminishes exponentially and it would be minor for bonding and moving abrasive particles. Hence, this method can only be used for plates. Electromagnets generate heat during the process, which can have a negative effect on the process for long processes, so there is a need for a cooling system.

4 Conclusion

In this research, a novel technique in the MAF is introduced to improve its potential by using traveling electromagnetic fields. The magnetic field is transmitted by using electrical and electronic techniques and could completely eliminate the need for mechanical machines. The proposed TMAF technique makes it possible to create special and different finishing patterns on the surface of thin sheets simultaneously by controlling the transmission of the magnetic fields and arranging the magnetic coils. Moreover, the experimental results show that the coil current revealed a significant effect on the surface roughness. And TMAF has the potential to finish free-form surfaces having no special fixture or machine tools, which extends the MAF potential for the automation process and makes it more flexible.

Author contribution Abbas Moghanizadeh contributed to study design, data collection, data analysis, interpretation of findings, and writing of the manuscript.

Availability of data and material There are no restrictions on the availability of data and material.

Declarations

Ethics approval Ethical approval was not required.

Consent to participate All participants provided informed consent to participate in the study.

Consent for publication The publisher has our consent to publish this manuscript including figures and associated data.

Competing interests The authors declare no competing interests.
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