A new strategy for improving the surface quality of Ti6Al4V machined by abrasive water jet: reverse cutting with variable standoff distances

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Abstract
Titanium alloys are widely used in important structures of aerospace vehicles, but the low thermal conductivity and high chemical activity make them difficult to process. As an untraditional machining technology, abrasive water jet (AWJ) has been proven to be an effective method for this kind of material. Aimed at further improving the cutting performance, reverse cutting with variable standoff distance (SOD) strategy was put forward, and experiments of titanium alloy Ti6Al4V machined by AWJ were conducted. The influence of SOD with different reverse cutting types on the kerf quality was studied, and the total height of the surface ($S_t$), the arithmetical mean deviation of the profile ($Ra$), the arithmetic mean and root-mean-square deviations of the surface ($Sa$, $Sq$), and the kerf taper ($\alpha$) were used to evaluate the cutting quality. It was found that the proposed strategy could result in a higher machining quality compared with the single cutting. More specifically, for the reverse trimming cutting, the highest of the striations characterized by $S_t$ could be reduced from 341 to 117 $\mu$m at traverse speed of 600 mm/min using this strategy. The improvements of $Ra$, $Sa$, and $Sq$ can reach up to 62.8%, 67.0%, and 57.2%, respectively, under the condition that the SOD of the second cutting is 8 mm. Furthermore, the kerf taper can be reduced 26.1% at SOD of the second cutting being 2 mm. With respect to the reverse deepening cutting, even the traverse speed of reverse cutting is set as twice as that of a single cutting, the kerf quality is still better. Additionally, when the SOD of the second cutting is 4 mm, the improvements of $Ra$, $Sa$, and $Sq$ can reach up to 51.7%, 34.3%, and 33.2%, respectively, and at the same time, the kerf taper is reduced by 20.2%.

Keywords Abrasive water jet · Titanium alloys · Surface quality · Reverse cutting · Standoff distance

1 Introduction
Titanium alloys (and more especially Ti6Al4V) are widely used in the aerospace industry for the excellent physical properties of strength to weight ratio, high thermal and corrosion resistance, and chemical inertness [1]. However, titanium alloys have low thermal conductivity and high chemical activity, making the cutting heat not easy to dissipate during the machining process. Thus, serious thermal impact, material modification, and adhesion to the tool are generated, which greatly increases tool wear [2].

As a non-traditional and high-energy beam processing technology, abrasive water jet (AWJ) removes material by the erosion process, wherein hard abrasive particles are suspended in a water jet stream of high velocity, which in turn increases the acceleration of the abrasive particles, and their kinetic energy impingement toward the target material, causing material removal [3]. Recent research conducted by Liao et al. [4] shows that AWJ is a particular non-conventional machining operation that can increase the material removal rate, especially for superalloys. Also, Hagbin et al. [5] claimed that AWJ can machine a wide range of ductile and brittle materials, and it has excellent characteristics such as high processing efficiency, no thermal effect, and environmentally benign. Moreover, it is demonstrated that AWJ cutting is superior to many other cutting technologies in processing difficult-to-cut materials such as titanium alloys [6]. However, the cutting performance of hard materials is still far from satisfactory, which greatly limits the applications of AWJ [7].
It is known that the kerf quality and the processing time of AWJ cutting significantly depend on the processing parameters and strategies [8]. Most of the previous studies on AWJ cutting are single cutting, and the main work done is to find the optimal cutting process parameters for different materials. For example, multi-pass cutting is a promising strategy for improving the AWJ cutting performance, and it represents a fertile field for more investigations, especially for the combined influence of the control parameters at consequent cutting passes on the output responses [9]. Hashish and Du Plessis [10] established a series of prediction equations to study the effects of standoff distance (SOD) and multi-pass strategy on the cutting depth, volume removal, and specific energy. It was found that there is an optimal SOD in the water jet cutting process, and multi-pass can effectively improve the cutting quality. Moreover, by focusing on the influence of the nozzle traverse speed and direction on the cutting performance, Wang [11] conducted experiments with alumina ceramic as the workpiece and analyzed the process of multi-pass cutting. The results show that multi-pass cutting is distinctly superior over the single pass cutting, which provides guidance for the selection of cutting parameters. Miao et al. [12] used AISI 304 stainless steel as the workpiece and studied the quality of the cross-sections under different cutting times. Through the experimental results, they found that the optimal number of cutting times is two passes, and the minimum taper angle can be obtained with three passes. Xiao et al. [13] discussed the multi-pass cutting effects on CFRP and made a comparison between the constant and the changed parameters. They found that multi-pass cutting could further reduce 53% of the kerf taper and improve the efficiency by 13% if appropriate parameters can be selected. In addition, Mesalamy and Youssef [14] investigated the influence of number of cutting passes, traverse speed, and cutting direction on the quality of cutting by using response surface method (RSM) and claimed that second pass is the key point to improve the surface quality.

Although numerous studies on multi-pass cutting have been conducted [15], few with variable SOD could be found in the literature, let alone for titanium alloys. The geometric features and dimensions that have been reported in the literature are mainly on deviations and taper angle. However, it can be noted that SOD is one of the most important factors in such regard [16]. So, in the present study, a new strategy of reverse cutting with variable SOD was put forward—cut twice at the same part of the workpiece by changing the traverse direction and SOD during the second cutting. Depending on whether the workpiece is cut through or not under one pass, reverse cutting was defined as reverse trimming cutting and reverse deepening cutting, schematically shown in Fig. 1. It can be seen from the figure in the second pass of reverse trimming cutting, only the edge part of the jet beam participates in the processing. The jet is far from the nozzle and is more divergent. Therefore, it is obvious that SOD can put a great impact on the area and effect of the trimming process. In the second cutting of reverse deepening cutting, the actual SOD becomes the distance between the nozzle and the processing bottom surface formed in the first cutting. Therefore, it should be necessary to study the influence of variable SOD on the machining quality.

The new strategy in this study was used to investigate the cutting performance on titanium alloy Ti6Al4V. At first, through the analysis of preliminary experimental data, the optimal SOD of AWJ cutting titanium alloy under the single cutting condition was explored. Then, the advantages of the reverse cutting with variable SOD strategy were verified. Finally, the effects of this strategy on the cutting kerf taper and the surface quality of the cross-sections were studied respectively, and the optimal parameters were obtained. This strategy can further improve the cutting performance and reduce the cutting time at the same time, and can also provide some guidance for processing other hard materials.

2 Experimental material and methods

2.1 Equipment

The experiments were performed on a five-axis abrasive water jet machine (Model: APW2016BA-18) shown in Fig. 2. The working pressure can be adjusted steplessly with
a maximum value of 420 MPa. For the cutting head, a ruby nozzle with a diameter of 0.33 mm and a focusing tube with a diameter of 1.02 mm and a length of 76.2 mm were used in the experiments.

The surface roughness of the machined specimens was measured by surface test equipment (Mitutoyo SJ-210, as shown in Fig. 3) and a 3D laser scanning optical profilometer (Nanofocus μscan Select, as shown in Fig. 4). The range of SJ-210 for the surface height measurement of the workpiece is 0–360 μm. It was used to get the $Ra$ at the measuring line of the surface. Nanofocus μscan select is an optical profilometer used for the three-dimensional measurement and surface analysis. Its resolution in the perpendicular direction is 35 nm. It was used to obtain the surface morphology and the amplitude parameters of the striations.

### 2.2 Material

Ti6Al4V, which is a typical kind of titanium alloy, was used as the test specimen in the experiments. The physical properties of Ti6Al4V are shown in Table 1.

### 2.3 Method

During the AWJ cutting experiment, the nozzle was perpendicular to the surface of the workpiece and maintains a certain value of SOD. The surface of the cross-section also shows different profiles, including initial zone, smooth zone, and rough zone. As the range of the initial zone is very small, it is usually not considered [17]. The smooth zone and rough zone are produced by particles impacting at shallow and large impact angle [18]. And the rough zone has obvious striation, which can be clearly distinguished, as shown in Fig. 5.

Since the surface of the cross-section after AWJ cutting is not uniform, other evaluation methods should be used to characterize the surface quality, except for $Ra$ (arithmetical mean deviation of the roughness profile, μm). According to the research of Sutowska et al. [19] and Romanowski et al. [20], amplitude parameters $Sa$ (arithmetic mean deviation of the surface, μm), $Sq$ (root-mean-square deviation of the surface, μm), and $St$ (total height of the surface, μm) were also used. The advantage is that the amplitude parameters are not affected by the result error caused by the measurement position and the scanning direction in the $Ra$ measurement.

$Ra$ was measured three times at the positions of 1 mm, 2.5 mm, and 4 mm from the upper surface of the workpiece, shown in Fig. 5. Two areas (4.8 mm * 6 mm) on the processed cross-section were selected at an interval of 10 mm for scanning, and $Sa$, $Sq$ were calculated by the following equations:
where $A$ is the height of the point $(x, y)$ on the surface.

In addition, kerf taper $\alpha$ was used to evaluate the kerf quality after processing. Due to the energy dissipation during AWJ machining, the kerf widths at the entrance and the exit are different as shown in Fig. 6. The entrance width and exit width are measured on three different locations of the kerf. The kerf taper $\alpha$ can be described by the following equation:

$$\alpha = \arctan\left(\frac{W_a - W_b}{2h}\right)$$

where $W_a$ is the entrance width of the kerf, $W_b$ is the exit width of the kerf, and $h$ is the thickness of the workpiece.

This study mainly focuses on the influence of changing SOD of the second cutting on the cutting performance under different traverse speeds. The constant parameters are shown in Table 2.

All experiments are conducted twice to minimize the equipment errors. In order to minimize the measurement error, the measured values of the processed surface were averaged first, and then the measured values of the two surfaces were averaged to obtain the experimental data. The error bars of each data in the paper represent the standard error of the measured values.
3 Preliminary tests

3.1 The range of traverse speed

A piece of Ti6Al4V with a thickness of 10 mm was used in the preliminary tests performed in advance, in order to get the appropriate parameters which were the working pressure, the traverse speed, and the SOD. The cutting depth against the traverse speed in the range of 400–1600 mm/min was obtained and shown in Fig. 7. This curve serves as an important reference for the selection of the later traverse speed in the study of variable SOD.

It can be seen that the cutting depth decreases with the increase of traverse velocity, but the decreasing trend becomes slow gradually.

3.2 The optimal SOD

It is known that there exists an optimal value of SOD, depending on the machining conditions [14]. Therefore, the optimal SOD for single cutting under the condition should be achieved at first. According to the curve in Fig. 7, when the traverse speed is 800 mm/min, the cutting depth is about 5 mm. The workpieces with a width of 50 mm and a thickness of 5 mm were used for the single cutting tests, and the parameters are shown in Table 3.

3.2.1 Surface quality

(a) Macroscopic analysis of the cross-section.

Nine cross-sections under the conditions of the SOD of 2 mm, 6 mm and 10 mm at three traverse speeds were used to analyze the surface characteristics. As can be seen from Fig. 8, the cross-sections of the workpiece after single cutting present obvious partitions. With the increase of traverse speed, the smooth zone decreases, and the surface deteriorates gradually. When the traverse speed is 800 mm/min, erosion pits and uncut parts appear on the surface, leading to a sharp decline in surface quality. Comparing the cross-sections under different SODs, it can be seen that the surface quality is worse when the SOD is too small or too large. Therefore, for a specific workpiece, there must be an optimal SOD to obtain the best surface quality. In order to obtain the optimal SOD, the surfaces were quantitatively analyzed by using $R_a$, $S_a$, and $S_q$ to characterize the cross-sections quality.

(b) Surface roughness analysis.

In order to acquire the optimal SOD for cutting titanium alloy under certain working conditions, the surface test equipment and 3D profilometers were used to obtain the data representing the surface quality of the cross-sections.

It can be seen from Fig. 9 that at the three traverse speeds, the $R_a$, $S_a$, and $S_q$ of the cross-sections are minimum when the SOD is about 6 mm. Moreover, with the traverse speed increasing from 400 to 800 mm/min, the minimum values of $R_a$, $S_a$, and $S_q$ increase from 4.32 to 10.31 μm, from 20.6 to 49.8 μm, and from 24.5 to 56.2 μm, respectively. As observed in Fig. 8, when the SOD is 6 mm, the smooth area of the cross-section is larger than that at the SOD of 2 or 10 mm. The reason for this result is that SOD has an important correlation with the divergence and energy distribution of AWJ. When the SOD is too small, the acceleration of the abrasive is insufficient, resulting in a weaker removal ability of the AWJ. On the other hand, the energy attenuation due to the friction between the AWJ beam and the air will also weaken the removal ability of the AWJ, if the SOD is too large. When the removal ability of AWJ is weak, it will enlarge the rough area of the cross-section and reduce the surface quality.

It is of great interest to find that the values of $R_a$, $S_a$, and $S_q$ increase with a higher traverse speed. More specifically,
at traverse speed of 800 m/min, the surface quality drops sharply. Combining the cross-sections in Fig. 8 for analysis, it can be claimed that when the traverse speed is small, the AWJ beam deflection during the cutting process is not obvious. So, most of the water and abrasive are ejected from the exit, which can obtain a cross-section of more regular and flatter striations. With the increase of traverse speed, the speed reaches the critical value that cannot cut through the workpiece. In this case, the deflection of AWJ is severe, and some random direction reflected jets are generated, which damages the machined surface, resulting in irregular erosion pits in the cross-section.

3.2.2 Kerf taper

A microscope was used to measure the widths of the kerf entrance and exit, and then calculate the kerf taper. It can be seen from Fig. 10a, the kerf taper increases as the SOD increases at different traverse speeds. For example, at a traverse speed of 600 mm/min, the kerf taper increases from 3.21° to 4.96° as the SOD increases from 2 to 10 mm, which is a significant increase.

According to the analysis in Fig. 10b, when the SOD is small, the jet divergence is slight, and the acceleration process of abrasive particles is short, which represents a weak cutting performance and forms a narrow entrance width. With the increase of the SOD, the jet diverges severely, and the removal ability becomes stronger, which forms a wider entrance width.

During the cutting process, the exit width is smaller than the entrance one because of the energy consumption of AWJ. Moreover, the dispersion and the consumption of AWJ energy increase with the increase of SOD. As a result, the high-speed abrasive particles participating in the cutting process gradually decrease with the depth of the cutting, and the exit width becomes narrower.

In more specific terms, when the SOD is 2 mm, the minimum value of kerf taper increases from 3.08° to 3.41° with the traverse speed increasing from 400 to 800 mm/min. Obviously, the increase of the traverse speed makes the AWJ cutting time shorter, which will inevitably lead to smaller jet energy and weaker cutting ability. Therefore, the faster the nozzle traverse speed is, the smaller the width of entrance and exit will be.

Taking surface quality as the first consideration, 6 mm was chosen as the SOD for the first cutting. Since the regularities obtained at the three speeds are the same, 600 mm/min is chosen as the traverse speed for subsequent experiments. Then, the traverse speed of 1200 mm/min was selected for comparison, which can keep the same processing time with the single cutting. The improvements of reverse trimming cutting and reverse deepening cutting on machining quality were studied respectively. The machining parameters in the experiments are shown in Table 4.
Fig. 9 Cross-section roughness of single cutting evaluated by (a) $R_a$, (b) $S_a$, and (c) $S_q$ at different traverse speeds and SODs.

Fig. 10 Kerf characteristics at different traverse speed and SODs, (a) kerf taper, (b) entrance width, (c) exit width.
Table 4  Experiment parameter

| Strategy                      | Reverse cutting | Reverse deepening cutting |
|-------------------------------|------------------|---------------------------|
| Traverse speed (mm/min)       | 600              | 1200                      |
| SOD in first cutting (mm)     | 6                | 6                         |
| SOD in second cutting (mm)    | 2/4/6/8/10       | 2/4/6/8/10                |

4 Results and discussion

In order to clearly show the effects of the new cutting strategy, the macroscopic characteristics of the cross-section surfaces under different machining strategies were analyzed at first. Then, the optimal process parameters were obtained by a quantitative analysis of the surface roughness of the cross-sections.

4.1 Macroscopic characteristics of the machined surfaces

The specimens with better surface quality after processing by the new strategy and the specimens after single cutting were used for comparative analysis. Use the three-dimensional profiler to scan and reconstruct the processed cross-sections; the surface morphology of the cross-sections can be obtained, as shown in Fig. 11. It can be found that when the traverse speed is the same as the single cutting, the processing method is reverse trimming cutting. Compared with the surface after a single cutting in Fig. 11a, the surface processed in the reverse trimming cutting (Fig. 11b, c) is quite flat, and the rough area on the surface almost disappears, except for a small number of residual striations near the exit of the kerf.

Taking both Fig. 11a, b into consideration, it can be seen that the highest peak of striations (given by amplitude parameter St) is reduced from 341 μm for single cutting to 174 μm for reverse trimming cutting. In addition, the residual striations are fewer, and the surface is smoother by appropriately increasing the SOD before the second cutting. As shown in Fig. 11c, the highest peak of striations is further reduced to 117 μm.

To keep the processing time the same as the single cutting, a traverse speed of 1200 mm/min was used in processing. In this case, because the traverse speed exceeds 800 mm/min, the workpiece is not cut through in the first processing, so the processing method is the reverse deepening cutting. In this way, the residual striations on the processed surface are also greatly reduced compared to a single cutting. However, the non-through cutting produces the pocket at the bottom of the kerf due to unordered jet upward deflection [16]. Hence, the kerf produced at the first cutting randomly presented different shapes that could influence the performance at second cutting such as the irregular pits randomly occurring at kerf wall. After the second cutting, the erosion pits formed in the first cutting was trimmed to some extent. From Fig. 11d, it may be observed that the highest peak of striations had a value of 218 μm, and the surface quality is still better than that of a single cutting. Moreover, comparing Fig. 11d, e, it can be seen that when the SOD reaches the appropriate value for the second cutting of reverse deepening cutting, the removal effect of the defects generated in the first processing is significant. The St of the surface in Fig. 11e is 160 μm, which is only half of the single cutting. Therefore, the surface quality of the cross-section after the cutting with the new strategy is far better than a single cutting.

4.2 Quantitative analysis of the machined surface quality

In order to quantitatively demonstrate the specific improvements of the reverse cutting with the use of the variable SOD strategy, the surfaces processed using different strategies were measured, and the results are shown in Fig. 12. For the two different processing types using the new strategy, the parameters for obtaining a higher machining quality are different, so the two types need to be analyzed separately.

Figure 12a shows that Ra values of the surface cut by the reverse deepening cutting method at the traverse speed of 1200 mm/min are between 3.3 and 4.5 μm. According to the standard definition, when Ra is 3.2 μm, the surface features are evenly distributed throughout the measurement area. As can be seen form Fig. 12b, c, the minimum values of Sa and Sq are 21.1 μm and 24.5 μm at traverse speed of 1200 mm/min. Compared with the traverse speed of 600 mm/min, the increases of Sa and Sq are about two times, which is in consistent with the actual situation of the processed surface. Therefore, it is more accurate to use the surface amplitude parameters Sa and Sq to characterize the quality of uneven surfaces.

4.2.1 The reverse trimming cutting

For reverse trimming cutting, the surface quality of the cross-section is directly related to the amount of trimming.
Fig. 11 Cross-sections of reverse cutting at (a) control group-single cutting of 600 mm/min and 6 mm, (b) reverse trimming cutting of 600 mm/min and 6-6 mm, (c) reverse trimming cutting of 600 mm/min and 6 mm-8 mm, (d) reverse deepening cutting of 1200 mm/min and 6-6 mm, and (e) reverse deepening cutting of 1200 mm/min and 6-4 mm.
Different jet divergence degrees get different trimming amounts, and the jet divergence degree is positively correlated with the SOD.

It can be seen from the Fig. 12 that compared to a single cutting with a traverse speed of 600 mm/min, when the SOD of the second cutting is 8 mm, the reverse trimming cutting has the best effect on improving the surface quality of the cross-section. The improvements of $Ra$, $Sa$, and $Sq$ are 62.8%, 67.0%, and 57.2%. In this case, the $Ra$, $Sa$, and $Sq$ of the cross-section are 2.59 μm, 10.6 μm, and 15.7 μm. However, if the SOD is not changed during the reverse trimming process, $Ra$, $Sa$, and $Sq$ only increase by 60.3%, 61.4%, and 52.3%.

The reason for the above results is that when the jet divergence is small, the contact area between the jet and the workpiece is small. As the SOD increases, the jet beam diverges significantly, and the trimming area is greater. When the SOD is too large, the jet diverges severely and damages the existing surface, causing the surface quality to degrade again.

4.2.2 The reverse deepening cutting

Reverse deepening cutting means increasing the cutting depth through the second cutting, so as to achieve the purpose of cutting through the workpiece. When the current traverse speed cannot cut through the workpiece at one time, the influence of the second cutting SOD on the cross-section quality was studied.

The measurement results of the cross-section are shown in Fig. 12. It can be seen that $Ra$, $Sa$, and $Sq$ are minimum when the SOD of the second cutting is 4 mm. When the SOD of the second cutting is further increased, the surface quality deteriorates.

While maintaining the same time as the single cutting with a traverse speed of 600 mm/min, the reverse deepening cutting with a traverse speed of 1200 mm/min was used for the processing. Compared with the single cutting, when the SOD of the second cutting is 4 mm, $Ra$, $Sa$, and $Sq$ obtain the best enhancement effects, which are 51.7%, 34.3%, and 33.2%, respectively. In this case, the $Ra$, $Sa$, and $Sq$ of the cross-section are 3.36 μm, 21.1 μm, and 24.5 μm. However, if the SOD of the reverse deepening cutting is kept unchanged, $Ra$, $Sa$, and $Sq$ only increase by 44.0%, 28.0%, and 24.3%, respectively.

4.3 Analysis of the kerf taper

As is shown in Fig. 13, by appropriately reducing the SOD of the second cutting, a higher cutting capacity can be obtained. The minimum kerf taper appears when the SOD of the second cutting locates in the range of 2–4 mm. As the SOD increases, the kerf taper becomes greater gradually.

Compared with the single cutting at traverse speed of 600 mm/min and SOD of 2–4 mm, it can be found that the

![Fig. 12](image-url)
kerf tapers of reverse trimming cutting and reverse deepening cutting are 2.90° and 3.13°, corresponding to the greatest improvements of 26.1% and 20.2%, respectively. However, if the SOD is not changed during the second cutting process, the improvements of kerf taper are 19.5% and 12.3%, respectively. Thus, it can be demonstrated that the proposed cutting strategy of variable SOD produces smaller kerf tapers, which contributes to higher cutting quality of AWJ.

5 Conclusion

In this study, a new strategy of reverse cutting with variable SOD has been applied to improve the cutting quality of titanium alloy machined by AWJ. As the SOD changes in the process of the reverse cutting, better cutting surface and kerf qualities were achieved. The main outcomes of this study are summarized below.

1. For processing methods with uneven cross-sections after processing, the commonly used center line average value parameter $Ra$ is not accurate enough to characterize the actual surface quality. The combination of $St$, $Sa$, $Sq$, and $Ra$ can make up for the deficiency of $Ra$ in characterizing uneven surfaces.

2. In the reverse trimming process, in order to obtain better cross-section quality, it is necessary to appropriately increase the SOD during the second cutting. In order to reduce the kerf taper, the SOD needs to be reduced during the second cutting. Under the condition when the traverse speed is 600 mm/min and the SOD of second cutting is 8 mm, the surface quality reaches its best. In this case, the $Ra$, $Sa$, and $Sq$ are 2.59 μm, 10.6 μm, and 15.7 μm, respectively. Compared to a single cutting at the same speed, the improvements of $Ra$, $Sa$, and $Sq$ are 62.8%, 67.0%, and 57.2%. When the SOD of the second cutting is 2 mm, the minimum kerf taper obtained is 2.90°, reducing 26.1% compared to a single cutting.

3. For reverse deepening cutting, in order to obtain the best cutting quality (including surface quality and kerf taper), it is necessary to reduce the SOD appropriately. When the traverse speed is 1200 mm/min, its cutting process maintains the same cutting efficiency as a single cutting of 600 mm/min. Under the circumstances, when the SOD of second cutting is 4 mm, $Ra$, $Sa$, $Sq$, and $α$ all achieve the minimum values, which are 3.36 μm, 21.1 μm, 24.5 μm, and 3.13°, the improvements are 51.7%, 34.3%, 33.2%, and 20.2%, respectively.

Author contribution Jie Xiong: conceptualization, investigation, and writing. Liang Wan: methodology and formal analysis. Yi’nan Qian: data collecting and editing. Shuo Sun: formal analysis. Deng Li: project administration, and writing-review and editing. Shijing Wu: supervision.

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Availability of data and material All the datasets supporting the results are included within the article.

Declarations

Ethics approval Not applicable.

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Consent for publication All the authors agree to transfer copyright of this article to the Publisher.

Conflict of interest The authors declare no competing interests.

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