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Effect of quenching media on mechanical properties of welded mild steel plate

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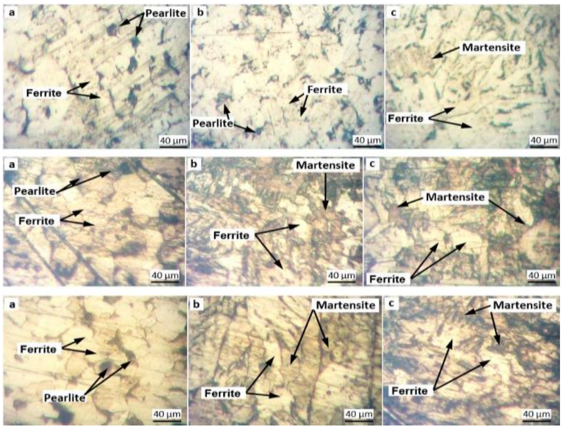

Highlights:

- The effect of quenching media on the microstructure and mechanical properties of mild steel plates was studied
- Microstructural analysis with hardness and impact tests was carried out with water, air, and oil as quenching media
- The quenching medium affects the microstructure of welded mild steel plate

Abstract

Quenching is a swift way of returning metal back to ambient temperature in order to acquire a certain property. Although it is often used to enhance the hardness of metals and their micro-structure, it equally causes a serious variation in the mechanical and physical properties of the metals. This research focuses on quenching media's effect on the microstructure and mechanical properties of a 150mm x 80mm x 8mm welded mild steel plate through microscopic examination, metallography mounting, surface grinding, and surface polishing. Microstructural analysis with hardness and impact test was carried out on the steel plate using water, air, and oil as the quenching media. The results of the test show the Vickers Pyramid Number (HV) for water, oil, and air to be 284.2, 270.9, and 262.2 HV for the base metal, heat affected zone (HAZ), and weld metal (WM), respectively. The amount of energy absorbed by the three specimens during fracture is 23.12, 25.27, and 26.83 J, respectively. The test further indicates that the water-quenched media exhibited mostly martensitic structures and held back austenite with many structures of cementite while the oil and air media exhibited martensite phase and refined grains structures individually. It is therefore concluded that air is more suitable to cool the weld metal for damping applications in engineering.

Keywords: Mild steel, Quenching media, Microstructures, Heat affected zone, Hardness

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1. Introduction

Welding is simply a process of joining metals together to ensure the continuity of the assembled materials. This process is done by melting together two similar metals with a filler material to form a pool of molten material, called a weld pool, which eventually cools, forming a strong joint [1]. Different sources of energy like a laser, gas flame, friction, and electric arc are welded and subjected to highly intense thermal excursions. This intense thermal energy requires different regimes of cooling – some of them are slow, others are fast (quenched) and a whole range in between [2]. Metal quenching is a swift way of returning metal back to ambient temperature in other to acquire a certain property. Despite the fact that it is often used to enhance the hardness of metals and micro-structure which sparks variance in the mechanical and the physical properties of the metal [3]. It is generally used to enhance the hardness of a metal. Metalworkers do this by setting the hot metal into a fluid or in some cases constrained air [3]. The few decisions of fluid or is alluded to as the medium. Normal media for quenching incorporate unique reason polymers, constrained air convection, freshwater, saltwater, and oil. Water is a powerful medium when the objective is to have the steel arrive at the greatest hardness.

In any case, utilizing water can prompt imperfection in metal. If outrageous hardness is not needed, mineral oil, whale oil, or cottonseed oil might be utilized in the quenching system all things being equal. The hot metal is being moved to the medium, steam ascends from the metal in incredible volume [4]–[6]. Motagi [7] performed some studies showing that low carbon steel such as mild steel can be fortified through heat treatment while extinguishing after heat treatment works on the mechanical properties of the steel. For most metallic materials, the high-cycle protections are overwhelmed by the strength and malleability, individually [8]. These advantageous traits must be accomplished through suitable heat treatment and quenching. Metal quenching processes involve heating above normal re-crystallization temperature while at a melting temperature. This temperature is maintained for a period of time to allow the heat to penetrate the material [9], [10].The metal is later quenched in a media in order to return it to room temperature. This process may be maintained for a period of time to allow uniform distribution throughout the metal structure.

The subject of mechanical testing of materials is a significant part of designing practice. Many researchers in the field of materials technology have proposed interesting works, but there is still much more work to be performed in this field, especially on mild steel. Alabi [11] studied the effect of water temperature on the mechanical properties of water-quenched medium carbon. Alvarenga [12] investigated the influence of carbide morphology and microstructure on the kinetic of superficial decarburization of C-Mn steels. Effects of processing parameters on the grain refinement of vanadium nitrogen micro-alloyed steels were also studied by Zhao [13]. Joshua [14] examined the effects of various quenching media on the mechanical properties of inter-critically annealed 0.26%C-0.83%Mn steel. Khera [15] investigated the various heat treatment processes on microstructure and hardness with respect to corrosion behavior for carbon steels. Hwang [16] performed some experiments to investigate the influence of Mo addition and austenitizing temperature on the hardenability of low-carbon steels. The effect of quenching media on the mechanical properties of medium carbon steel was also investigated by Zainulabdeen [17].

As it is known, mild steel is used in industry for various applications such as the fabrication of machinery parts where strength and hardness are required, automotive doors and castings, domestic appliances, hot metal ladles, and ship hulls [18], just to mention a few. Therefore, this paper presents the effects of quenching media (air, water, and oil) on the mechanical properties of welded mild steel plates.

2. Methods

2.1. Materials preparation

Mild steel is carbon steel with low carbon content ranging between 0.05% to 0.25% by weight. Though high carbon steel ranges from 0.30% to 2.0% carbon and if it is beyond 2.0% carbon, it is classified as cast iron. The two processes involve a combination of iron and coal melted together in a blast furnace, which then solidifies into a rectangular shape. The mild steel plates are welded with an arc welding machine. The eighteen mild steel plates that were cut by the guillotine machine were welded in pairs to make nine pieces in total. The mechanical properties of the specimens are determined by using a universal tensile testing machine for tensile testing and Vickers hardness apparatus for hardness testing. ASTM A36 is the most used mild and hot-rolled steel. It has excellent welding properties and it is suitable for grinding, punching, tapping, drilling, and machining processes [19]. **Table 1** gives the chemical composition of ASTM A36 mild steel and **Table 2** shows the mechanical properties of the mild plate obtained by using a universal tensile testing machine.

Table 1. Chemical composition of ASTM A36 Mild Steel [19]

Elements	C	Fe	Cu	Si	Mn	S	P
Mild steel (% wt)	0.25-0.29	98	0.20	0.28	1.03	0.05	0.040

Table 2. Mechanical properties of the ASTM A36 Steel and Experimental results comparison [20], [21]

Mechanical properties	ASTM specification	Experimental result
Ultimate tensile strength (MPa)	400-450	400-560
Yield tensile strength (MPa)	250	300
Elongation at break (%, 50 mm)	23	10-14
Hardness Vickers Number (HVN)	168.99	276.2

2.2. Welding process

Single V Groove butt joint was used when welding the mild steel plates. The base metal is ASTM A36 mild steel and 150mm x 80mm x 8mm in dimension, and the schematic illustration and dimensions of the welding process and Izod test specimens are shown in **Figure 1**.

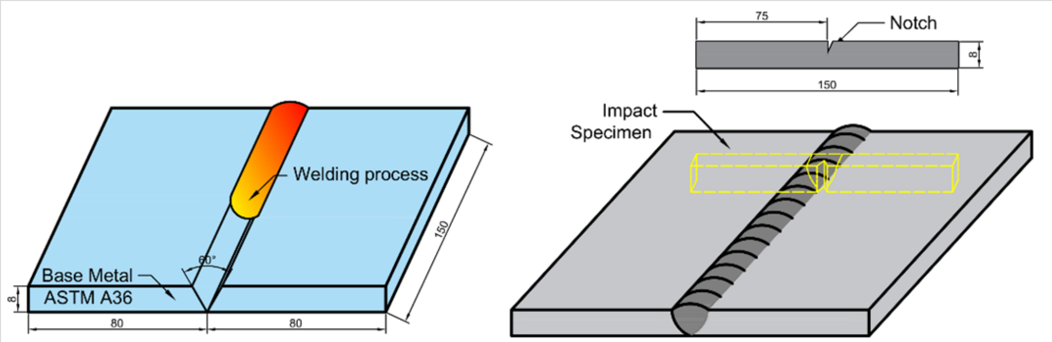

Figure 1. Schematic diagram of the welding process, welding specimen dimension, and impact test specimen (dimensions in mm)

2.3. Observation welded specimen's microstructure

Microstructure of the weld have observed and analized by microscope. There are four basic processes carried out during microscopic examination of welded mild steels: sample cutting, sectioning, mounting and surface grinding/polishing. The grain sizes of the phases were measured, and the microstructure of the specimens was examined before and after quenching process.

2.4. Impact test

The Izod impact strength test is an ASTM standard method frequently used to determine the impact toughness of materials, where the test conditions are generally governed by many variables, such as dimensions of the sample below the notch usually rectangular cross-section, velocity at the impact, mass of the hammer, curvature of the notch and temperature of the sample, as presented in **Figure 2**. Izod 9000 series impact test machine is used for this test. It is designed to perform Izod impact tests on a wide range of samples from bars/dumbbells to pipes in accordance with specific standards [22]. Also, it offers impact energy up to 50J with a range of options available. Impact energy is a measure of work done to fracture a test specimen. The specimen absorbs energy when it is struck by a hammer until it yields. Tougher materials have higher impact strengths while brittle materials have low impact strengths. To perform this impact test, the specimens are prepared before manufacturing them according to the standard of ASTM E23. The sample is placed into a holding fixture with the geometry and orientation determined by the type of test that is used. An object with a known weight and height is released to impact a sudden force on the specimen. This sudden impact helps to determine the actual behavior (toughness or brittleness) of the specimen. The energy required to break the specimen is recorded and the subsequent impact strength is calculated. The test was carried out at the ambient temperature between 31 and 34 °C in accordance with Zainulabdeen study [17].

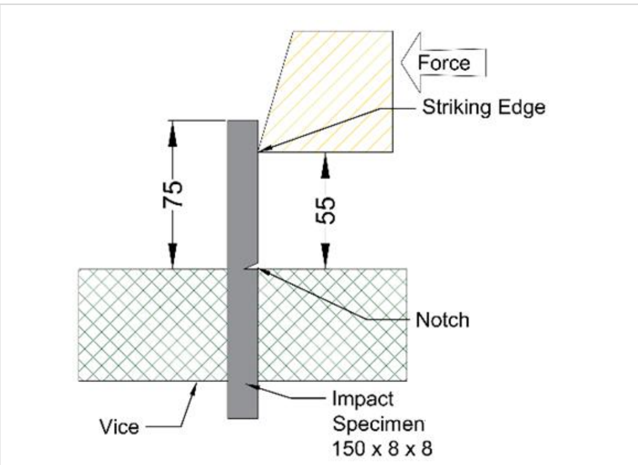

Figure 2. Izod impact test setup and dimmensions (in mm)

2.5. Hardness test

ASTM E384 standard is used for hardness tests and specimens are grinded and polished mechanically. The grinding is made by emery paper (320, 500, 1000 µm) in size, while the polishing is made by using wool cloth and alumina (1µm) in size. Microscope equipment allows for precise indentation placement. In this test, the hardness of the specimens was determined by measuring accurately with the aid of MMT-X7A Micro-hardness tester. Small indentations were produced by the application of 300 N for 15 s. In order to obtain reliable statistical data, analysis points were spaced so as to eliminate the effect of near indentations. Three indented samples were evaluated, and their averages were calculated. The position of the welding hardness data collection point is depicted in **Figure 3**.

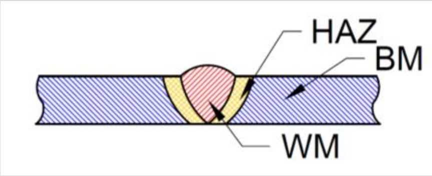

Figure 3. Position of hardness test on welding result

3. Results and Discussion

Table 3 shows the results of the micro-hardness test carried out on welded mild steel plates. The unit of hardness given by the test is known as the Vickers Pyramid Number (HV) since the Vickers hardness tester was used. It can be perceived that the hardness of the base metal is higher than the heat-affected zone (HAZ) and weld metal (WM). The hardness at the heat-affected zone (HAZ) is higher than that of the WM. The highest hardness occurs in BM because ASTM A36 mild steel is rolled plate. The microstructure of the rolled plate is denser and flatter in cross-section as shown in **Figure 4**. The decrease in hardness values in HAZ and WM was caused by the influence of heat input during the welding process. Heat input provides a lot of heat in WM even through the melting temperature of base metal so that it changes its microstructure. After going through the welding process, the HAZ changes its hardness to become softer because the shape and grain size are normalized.

Table 3. Results of the micro-hardness test of the welded mild steel

Samples	1 (HV)	2 (HV)	3 (HV)	Average (HV)
Base Metal	276.2	283.4	269.1	276.2
HAZ	265.3	271.7	262.8	266.6
Weld Metal	252.1	255.3	249.5	252.3

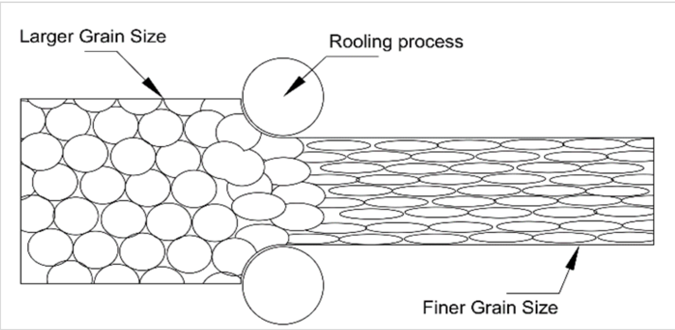

Figure 4. Rolled plate schematic

3.1. Hardness of the different quenching media

Table 4 demonstrates that the hardness of base metal of the three different quenched sheets of steel is higher than the heat-affected zone (HAZ) and weld metal (WM). The hardness BM, HAZ and WM of water-quenched steel is higher than that of oil-quenched steel and air-quenched steel. This hardness result is because the high heat input affects WM's microstructure to transform and then not have time to return to its original structure due to rapid cooling process. Martensite is formed in WM/WC due to temperature increases past the melting point and rapid cooling [23]. This hardness result is because the high heat input affects WM's microstructure to transform and then not have time to return to its original structure due to the rapid cooling process. Martensite is formed in WM/WC due to temperature increases past the melting point and rapid cooling. Martensite has hard and brittle properties, so the presence of martensite can increase the hardness of the weld [24].

Table 4. Effect of quenching media on hardness using the quenched mild steels

Samples	Water Cooled (HV)	Oil Cooled (HV)	Air Cooled (HV)
Base Metal	291.70	284.80	276.20
HAZ	280.50	266.60	265.60
Weldment	269.80	264.70	252.10

Martensite is formed when the temperature is hot enough, but when rapidly cooled (with water and oil) the WM microstructure cannot return to its original state and leaves the martensite structure to be solid. The hardness value in WM is influenced by how much martensite is present. The more martensite, the harder the WM [25]. The highest hardness value occurs in WC, this is due to a large amount of martensite left behind due to rapid cooling. In the OC process, the WM microstructure has time to change back into ferrite and pearlite but also leaves martensite. This causes the hardness value of OC to be higher than AC.

3.2. Toughness of different quenching media

Figure 5, **Figure 6**, and **Figure 7** show the graphical representations of results for micro-hardness tests, hardness of the quenched mild steel, and impact tests of the samples, respectively. Welded and quenched mild steel with water and oil form a martensite microstructure. Martensite is more brittle and harder than pearlite and ferrite, so its toughness increases when martensite is present in welding. The more hardness and martensite, the higher the hardness value, as well as the brittleness. The results of WC and OC prove that the quenching process increases the toughness value of the weld. The toughness of OC specimens is higher than WC, this is due to the presence of more martensite in the welds carried out by the rapid cooling process [26]. Martensite that has formed during the welding process does not have enough time to return to the ferrite and pearlite structure at the rate of decreasing temperature in the WC. On the other hand, the OC process results in a rapid decrease in temperature which can result in some of the microstructures returning to ferrite and pearlite, but there is still the presence of martensite. The combination of martensite, pearlite and ferrite at OC produces higher toughness. Then, **Table 5** shows that the force required to break the third sample is higher than the other two samples. The amount of energy absorbed by the first specimen during fracture is 23.12 J, the second specimen absorbed 25.27 J, while the third specimen absorbed 26.83 J during fracture. The impact test shows that the impact failure reduces gradually. The value of impact toughness on the welding results is influenced by the microstructure of the welding results.

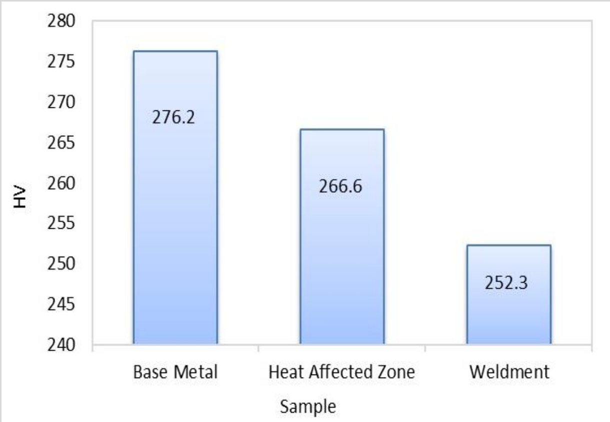

Figure 5. Graphical representation of micro-hardness testing

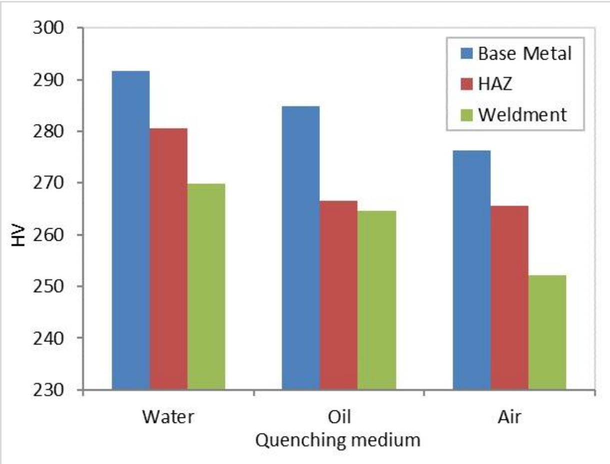

Figure 6. Hardness of the quenched mild steel

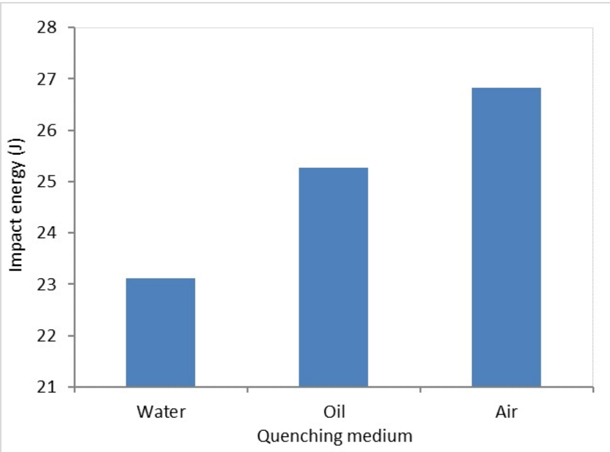

Figure 7. Graphical representation of the impact test on the samples

Table 5. Results of the impact test of the quenched specimens

Samples	Air Cooled	Water Cooled	Oil Cooled	Average
Energy (J)	23.12	25.27	26.83	25.07

3.3. Microstructure examination

Mild steel experiences a very rapid rate of cooling when quenched. Generally, quenching improves the performance of metals by rapidly cooling the heated metal thereby altering its molecular structure and increasing its hardness. Depending on the carbon content and alloying elements of the steel, it can be converted to a variety of microstructures during quenching. These microstructures result in increased strength and hardness for steel. **Figure 8**, **Figure 9** and **Figure 10** show the microstructures of the specimens after quenching in different quenching media. It was observed that water quenched sample showed predominantly martensitic structures and retained austenite with various morphologies of cementite. The volume fraction of martensite increases with increase in water quenching temperature. The microstructure of the specimen quenched in oil is composed of martensite phase only. It was also observed that oil exhibits a slower rate of cooling compared to water but faster than air.

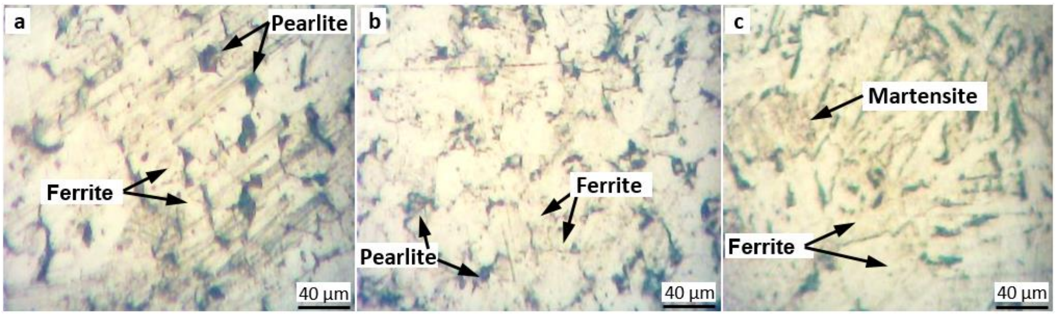

Figure 8. Air quenching process: (a) BM; (b) HAZ; (c) FZ

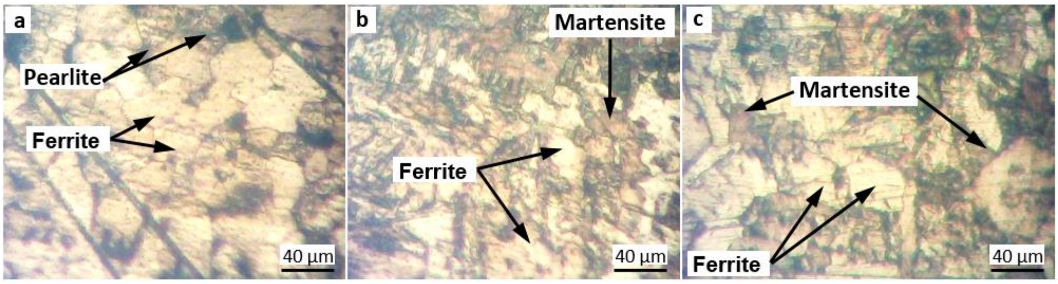

Figure 9. Water quenching process: (a) BM; (b) HAZ; (c) FZ

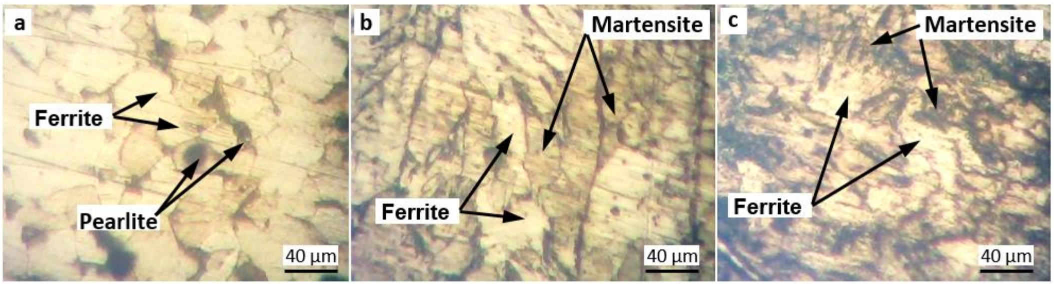

Figure 10. Oil quenching process: (a) BM; (b) HAZ; (c) FZ

4. Conclusion

The specimen quenched in oil withstands the increase in loads. Whilst the highest hardness which obtained for the specimen quenched in water is attributed to the hardness which increases with the increase in the percentage of carbon dissolved in austenite before quenching. The specimens after quenching in the selected quenching medium would have transformed from austenite to martensites. Martensite phase has a fine structure which is hard and very strong. The hardness of the specimen quenching in water has a higher value than in oil and air. This is due to the higher amount of the harder martensite in the treated steel; the austenite is transformed to martensite by the diffusionless transformation in quenching.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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