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RESEARCH ARTICLE

Fabrication of aneurysm blood vessel silicone phantom using 3D printed semi-reusable mould

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ABSTRACT - Aneurysms are vascular diseases with a low survival rate. Studying blood flow characteristics is essential to understand the disease, which would require experimentation on an anatomical phantom structure for simulating and measuring blood flow under controlled conditions. Conventional phantom fabrication often relies on single-use moulds, which are economically ineffective and time-consuming especially when replication is needed. In this study, we developed a method for fabricating an aneurysmal vascular phantom using a 3D-printed semi-reusable mould. The novelty lies in the reusable outer mould cope that was 3D-printed using polylactic acid (PLA), while the inner core was 3D-printed using water-soluble polyvinyl alcohol (PVA). A silicone-based elastomer, Sylgard 184 was used to create the vascular phantom because it approximates the mechanical properties of actual blood vessels. The silicone was injected onto the mould and the PVA core was dissolved in hot water to create a hollow structure. The resulting phantom is elastic and translucent, suitable for macro-scale flow visualization. It is also fabricated at a lower cost than those reported in previous studies. The semi-reusable mould concept enhances scalability by being low-cost and enables repeatable phantom production, offering an efficient way for research, training, and medical device testing.

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1. INTRODUCTION

Vascular diseases such as aneurysms can be extremely difficult to comprehend due to the complexity of the mechanical structure of the vascular system, which includes the vessel wall composed of multiple layers of tissue, and blood flow that transports a variety of important chemicals such as oxygen, protein, nutrients, and ions throughout the entire human body [1]. Due to the vital role played by this vascular system in our bodies, vascular illnesses such as aneurysms that affect major blood vessels in the brain and heart may have life-threatening consequences. According to the Brain Aneurysm Foundation, 500,000 people die each year from intracranial aneurysms throughout the world, with over half of these people being under the age of 50 [2].

Due to the complexity of elucidating the mechanism of vascular diseases, a vascular phantom is often used for experimentation on the vascular structure [3]. Phantoms can be fabricated in idealized shape, such as cylinders [4, 5] or using patient-specific shape generated from medical images such as computerized tomography (CT) scans and magnetic resonance imaging (MRI) [6, 7]. The general characteristics of the phantom for it to be used in experiments are it must mimic the mechanical properties of the actual blood vessels and it must be transparent to allow for the visualization of fluid flow in the phantom [8]. However, directly printing the phantom using a 3D printer may produce a rigid structure and low transparency. An elastic polymer is favourable for phantom fabrication to obtain reasonable stiffness to actual vessel. There are various types of elastic polymer with transparent properties that are suitable for producing vascular phantoms for fluid flow experiments, including poly (vinyl alcohol) hydrogel (PVA-H) [9], silicone [10], and polydimethylsiloxane [6, 7].

There have been various methods developed to fabricate vascular phantom. The first method is mould dipping technique. It begins with the desired mould with blood vessel shape is fabricated using a rapid prototyping machine. The mould is then dipped in a polymer liquid such as silicone or latex several times to coat its surface. The coat is left to cure, and the mould is removed afterward [11]. However, this method produces phantom with uneven thickness [12]. Second approach is to use lost core method. In this method, the wax core is fabricated following the shape of the desired phantom and then the phantom is fabricated using the mould dipping technique. The core is then removed via heating or using solvent, leaving a hollow cavity on the phantom [13]. Normally, a suitable core material, such as PVA is chosen to ensure that the core can be dissolved in water to reveal the phantom. The lost core can also be produced using acrylonitrile butadiene styrene (ABS), which can be dissolved in acetone. However, the wax lost method allows for a single time use only [10]. Third approach for phantom fabrication is via direct 3D printing using soft elastomer. This technique enables the fabrication of phantom with high geometric accuracy [14]. The limitation of this technique, however, is that it uses

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materials that are stiffer than the actual arteries [15]. Lastly, the phantom can also be fabricated using injection moulding, but it is expensive and less efficient for fabricating a one-off patient-specific phantom model [16].

This phantom can be used to simulate blood flow using artificial blood-like fluid in a mock circulation loop [17]. While computational methods are the used for simulating blood flow, validation is often required to increase confidence in the model [18-20]. The flow profile can be viewed using a method known as the particle image velocimetry (PIV), where particles are streamed into the flow and tracked via high-speed camera. For such application, the phantom must be transparent for the camera to capture the motion of the particles inside the phantom [10, 21]. Several past PIV experiments have been used to uncover mechanism of vascular diseases such aneurysm [22]. Nonetheless, the typical approach of constructing the phantom is often for single usage mould only, where the lost core method is often used. This technique requires further attention to produce a low-cost mould to avoid wastage.

In this paper, we described a method to fabricate silicone phantom using 3D printed mould part. The novelty in our method lies in the partially reusable mould concept, which reduces the need for re-printing of some parts while using dissolvable parts to produce inner cavity of the blood vessel structure. This article is organized as follows: (1) Methodology, which describes the process of mould development until the phantom fabrication process; (2) Results, which presents the analysis of the developed mould and phantom; (3) Discussion, which presents the advantages, limitations, and suggestions of future work; and lastly (4) Conclusion, which summarises the findings.

2. MATERIALS AND METHODS

2.1 Vascular phantom Structure

In this study, two types of idealized vascular phantoms will be fabricated, which represent a normal and aneurysm blood vessel. The aneurysm vascular phantom follows a saccular aneurysm shape with a diameter of 36 mm, the aneurysm height-to-neck ratio of 1.5 with the neck diameter of 24 mm, and the aneurysm width-to-neck ratio of set to 1.9 with the width of 45.6 mm.

Figure 1 shows the two mould designs. The mould has 3 components, which consists of the cope, core, and drag. A frame guides are included on each edge of the mould to ensure the mould is correctly positioned during the assembly. In addition, small holes were drilled onto the mould parts (not shown in Figure 1) to make the process of silicone liquid injection easier and to reduce the possibility of air bubbles formation in the phantom [21].

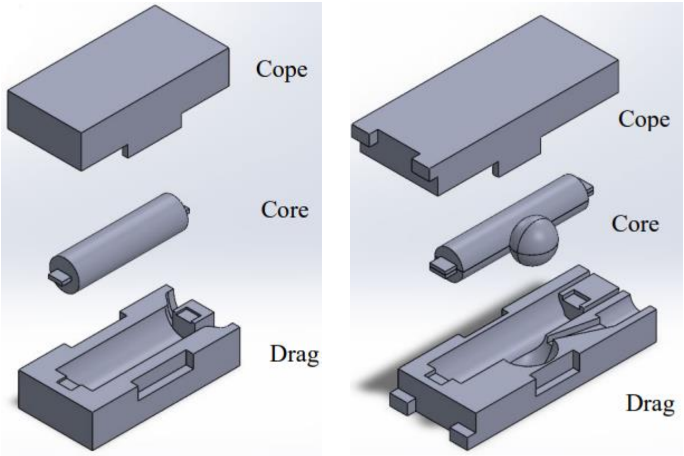

Figure 1. 3D CAD model of moulds: (left) normal blood vessel; and (right) aneurysm blood vessel

2.2 Material and Fabrication Process

The drag and cope components of the mould were printed using PLA filament. Meanwhile, the core for normal vascular phantom can be fabricated using PLA filament because it does not need to be dissolved. On the other hand, the core for aneurysm vascular phantom is fabricated using PVA filament, which is water soluble. All the moulds are printed using Ultimaker 3D printer (Ultimaker B.V., Netherlands). The printed structures are shown in Figure 2.

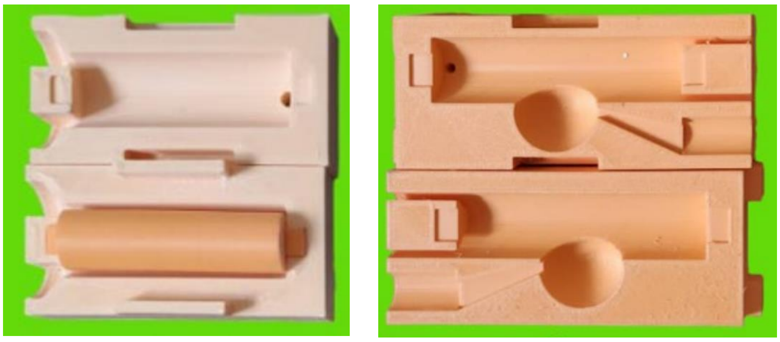

Figure 2. 3D Printed PLA outer mould: (Left) normal blood vessel with the inner core; and (Right) aneurysm blood vessel without the inner core

The inner mould surfaces must be smoothed using a sandpaper (aluminium oxide 3000 grit) as shown in Figure 3, to ensure that the phantom has better translucency. Afterward, the inner surface was sprayed using a silicone mould-release agent Koya P-651 (Tlc-Koya Chemicals Manufacturing, Malaysia) to facilitate easy phantom removal. The core structure is placed onto the drag part, glued, and the entire mould structure is clamped, as illustrated in Figure 4.

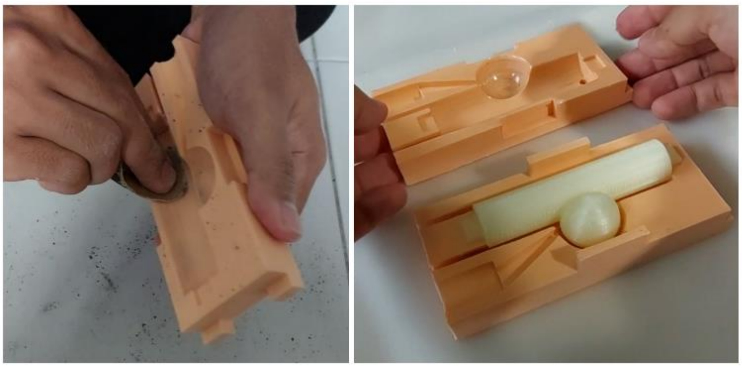

Figure 3. (Left) Sanding process; and (Right) PVA core in the aneurysm phantom mould

Figure 4. Mould assembly secured with clamps prior to injection

The silicone-based elastomer Sylgard 184 (Dow Corning Co., USA) is used for fabricating the phantom. The silicone is mixed with a hardener in a ratio of 10:1. The mixture is gently stirred for 5 minutes before being taken out using a syringe. The silicone mixture is then injected through the inlet hole on the mould until excess silicone is poured through the outlet as shown in Figure 5. The silicone is left to harden for two days to form the vascular phantom as shown in Figure 6.

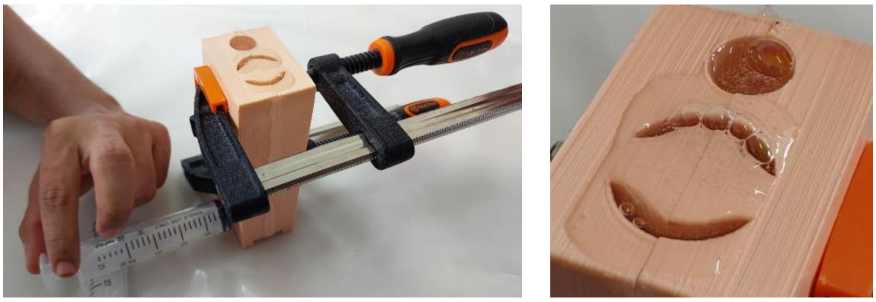

Figure 5. (Left) silicone is poured into the mould using a syringe pumped through a hole; and (Right) the excessive silicone is exuded out through the mould to ensure no bubbles are formed inside

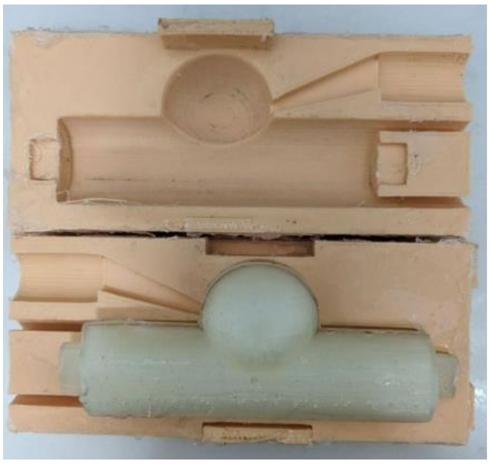

Figure 6. Hardened silicone after mould opening

After the silicone is hardened and removed from the mould, the core must be removed to produce a hollow vascular phantom. For the normal vascular phantom, the PLA core can simply be removed by applying a gentle force along the hollow direction. Meanwhile, the PVA core used in the aneurysm vascular phantom can be removed by dissolving it hot water bath at a temperature just below boiling point for four days, to ensure the PVA has fully dissolved. Figure 7 shows the final phantom produced.

Figure 7. (Left) Normal vascular phantom; and (Right) aneurysm vascular phantom

2.3 Mechanical Testing

A tensile test is performed to investigate the mechanical properties of the Silicone Sylgard 184 used for the phantom fabrication. It is carried out using the Instron Universal Testing Machine (Instron Corp, USA), with a maximum load capacity of 50 kN. The mechanical properties of the silicone were analysed through the stress-strain curve generated by the tensile machine. Furthermore, the tensile test sample is prepared following the American Society for Testing and Materials (ASTM) standard D638, as shown in Figure 8. A separate mould (not shown in this article) was produced to fabricate the test sample.

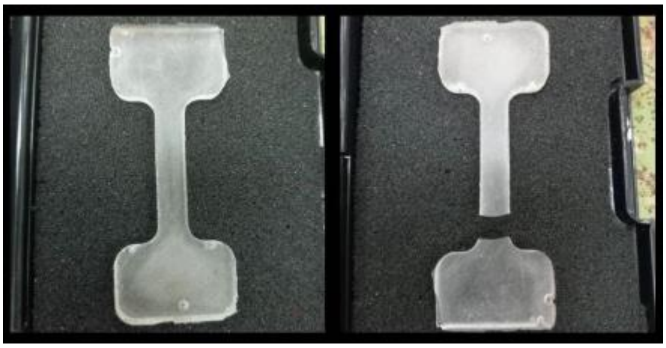

Figure 8. (Left) Test sample of silicone Sylgard 184; and (Right) test sample after the tensile experiments

3. RESULTS AND DISCUSSION

3.1 Qualitative Evaluation of Vascular Phantoms

Silicone Sylgard 184 elastomer is chosen because it is colourless, which allows for visualizing fluid flow inside the vascular phantom, especially in PIV experiments [17]. However, the surface of the final phantom appeared slightly tinted and hazy. The potential cause for this is that the surface of the mould is not perfectly smooth, which created a pattern on top of the vascular phantom surface. This is also the limitation of using FDM [23].

To ensure a better surface quality of the phantom, the PVA core must be fabricated with 100% density to reduce the number of voids or pores in the structure. However, the PVA core produced here has only 80% of the final density, which may allow the silicone to diffuse into the core. This is also a reason that contributes to the slight haziness of the phantom. However, the dissolution time took about 8 hours in boiling water and about 4 to 5 days in water at room temperature. Using a 100% density PVA core would produce an even longer dissolution time.

The silicone phantom tended to adhere to the mould surface and could tear during the removal. Figure 9 shows the examples of the phantom produced without and with the application of the releasing agent. Therefore, a suitable releasing agent is required to facilitate demoulding [24].

Figure 9. Final phantom produced: (Left) without the application of release agent; and (Right) with the application of the release agent

3.2 Mechanical Properties of Silicone Mixture

Figure 10 shows the stress-strain and load-displacement curves for the silicone Sylgard 184 obtained from the tensile tests. From these figures, the yield point obtained for Sylgard 184 is 2.28 MPa. As the load increases above this point, the specimen continues to undergo plastic deformation. At this point, the stress reaches the ultimate tensile strength of 2.84 MPa, in which after this point the material exhibits permanent deformation. The Sylgard 184 breaks as it reaches the ultimate tensile strength.

One limitation from the tensile test is to validate whether the silicone used exhibits similar mechanical characteristics as the blood vessels. Sylgard 184 is widely used to mimic the mechanical properties of cardiovascular phantoms [25]. The elastic stiffness obtained from the tensile test is 2.58 N/mm, which is about twice the typical elastic stiffness of Sylgard 184. Moreover, the elastic stiffness of the phantom obtained is also about 2.5 times bigger than the stiffness of human blood vessels, which should be within the range of 0.2 to 0.6 MPa [26]. The silicone phantom fabricated here is intended to have higher stiffness to ensure easy removal of the final product from the mould. The stiffness of Sylgard 184 is known to depend on the silicone-hardener ratio [27] and the curing temperature [28].

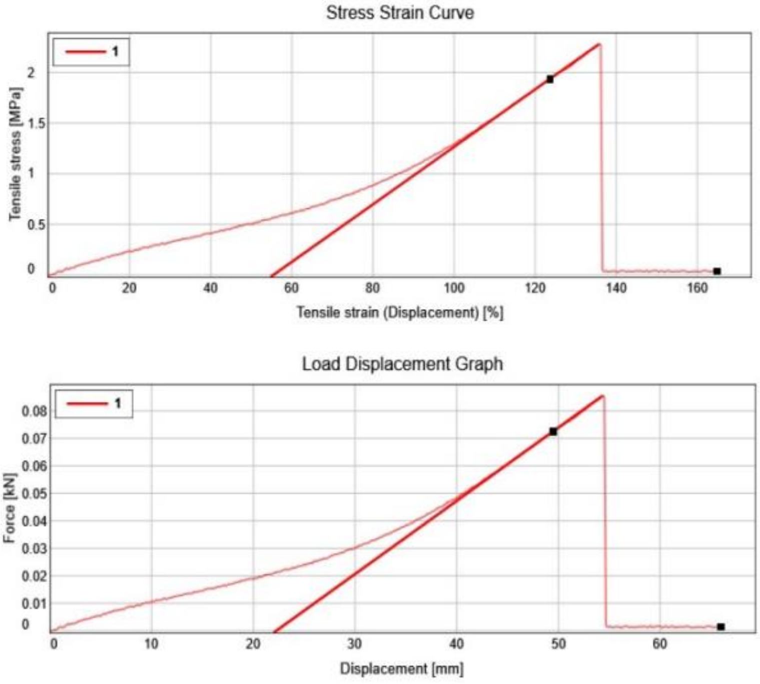

Figure 10. (Top) Stress-strain curve; and (Bottom) force-displacement curve

3.3 Costing

Another important criterion for fabricating the phantom is cost, which should be kept low. It should be cheaper to produce. The core is essential to fabricate a hollow phantom. Hence, it is the crucial part and the most expensive because it must be dissolved to obtain a hollow phantom. Table 1 shows the overall cost for producing a single aneurysmic phantom, which is MYR32.17. The cost for producing the reusable drag and cope components is only MYR4.00. Meanwhile, the cost for producing the non-reusable core is MYR9.00.

Comparing the pricing to fabricate the vascular phantom with some of existing studies, the phantom fabricated in this study is relatively cheaper. Table 2 shows the cost comparison between this study and previous studies. The sacrificial mould technique used by [29, 30] has similar concept as the lost core technique, but the vascular phantom is embedded in a scaffold.

Table 1. Cost of building the phantom in Malaysian Ringgit (MYR)

Material / Item	Unit price (MYR)	Package quantity	Quantity used	Cost incurred (MYR)
PVA filament	250.00	750 g	27 g	9.00
PLA filament	80.00	1000 g	50 g	4.00
Sylgard 184 elastomer	629.00	500 g	15 g	18.90
Mould releasing agent	7.30	500 ml	20 ml	0.30
			TOTAL	32.20

Table 2. Cost comparison of the phantom in Malaysian Ringgit (MYR) (rounded to nearest whole number)

Study	Price/unit (MYR)	Technique used
Current study	33.00	Lost core
Coles-Black *et al.*, 2021 [3]	100.00 – 5,000.00	Direct 3D printing
Nilsson *et al.*, 2022 [30]	70.00 – 350.00	Sacrificial mould
Laughlin *et al.*, [29]	350.00 – 1250.00	Sacrificial mould

3.4 Usability, Limitation, and Future Improvement

Vascular phantom is useful for medical research and educational purposes such as for stent insertion training [11, 31] and for surgical training [3]. A semi-reusable mould is beneficial in producing the phantom as it is cheaper and producing less waste, compared to a single-use 3D-printed mould [10]. In addition, other phantom fabrication method often requires the mould to be dissolved in a large amount of acetone or plastic solvent, in which the process must be done in a fume hood for safety reasons [10]. Here, the proposed method uses water-dissolvable core, which offers a safer alternative. The method also utilizes the same cope and drag for fabricating the next phantom, which reduces the time for replication of structure. Our technique could also be improved by implementing the 3D-printed mould as an insert for the injection moulding process for a fast and large-scale production [32]. The protocol developed here also relies on simple and readily available material, which can be procured at inexpensive cost as shown in the Table 1. The main innovation here is on the use of both non-dissolvable PLA component as the cope and drag, and dissolvable PVA as the inner core to create a semi-reusable phantom mould. This ensures replicability without the need for reprinting of the outer core.

Another challenge in producing the phantom is to ensure its translucency, which depends on the mould roughness and the stickiness of the silicone on the phantom. Currently, the inner surfaces of the mould were sanded with sandpaper to reduce its roughness. While this has improved the surface roughness, it might not be sufficient for several application where smoothness is necessary. For example, in any fluid-based experiment, the rough surface can induce turbulence boundary layer, which may cause inaccuracy especially for physiological flow measurements. This can be addressed by dipping the 3D-printed parts into acetone or plastic solvent to produce an even smooth surface [10]. In addition, surface roughness quantification using a surface profiler could be performed for better understanding of its effect on the phantom. However, due to the circular nature of the phantom, the quantification might be difficult as the measurement setup requires a flat surface [33]. Moreover, the current phantom is also translucent, which can be an issue if translucency is necessary, such as in particle image velocimetry experiment. While the current phantom is translucent, optical clarity for PIV can be achieved by using a blood-analog fluid that matches the refractive index of Sylgard 184 (RI ≈ 1.41), such as a glycerol-water mixture. Another factor that may contribute to the surface translucency is the number of trapped bubbles within the phantom. This can be resolved by infusing the mould with silicone within a vacuum chamber [34].

The vascular phantom fabricated has a mechanical property like a soft rubber. Further mechanical tests are required to fabricate a phantom mimicking the actual human blood vessel [35]. The findings obtained here show that the silicone mixture used has about twice the recommended mechanical properties of Sylgard 184, which means that a carefully tailoring the silicone phantom mixture is important for fabricating phantom with similar mechanical property as the actual blood vessel [27, 28]. Other considerations should also be taken. For example, the phantom design must be able to be fixed on both ends for the PIV experiments. The work done in [17] has included a specialized part in the mould to produce a fixator on the phantom for PIV experiment.

Despite the limitations found from the phantom fabricated in this study, several considerations have been considered during the fabrication process. The main goal is to produce cost-effective the vascular phantom using semi-reusable mould. Future work will focus on investigating materials with properties closer to human blood vessels [8].

4. CONCLUSIONS

A semi-reusable and cost-effective moulding method has been developed for the fabrication of an aneurysm vascular phantom. The key contribution here is the combination of non-dissolvable PLA mould with a water-soluble PVA core, which enables repeated use of the outer mould to produce hollow phantoms. The cost analysis shows that the fabricated phantom can be produced at a cheaper cost than previous studies. The phantom was fabricated using Sylgard 184, which is elastic and transparent, suitable for flow visualization experiment such as using PIV. The tensile test confirmed that the phantom produced has mechanical stiffness within an acceptable range for vascular phantom, although higher than the actual, but the purpose was to ensure durability and ease demoulding. This study demonstrates that a semi-reusable mould concept can reduce fabrication cost, minimize material waste, and improve replicability compared to conventional single-use moulds. The approach provides a practical and scalable option for producing vascular phantoms for haemodynamic experiments, training, and medical device testing. Future work will focus on optimizing surface smoothness, enhancing transparency, and tailoring mechanical properties to better match real human vessels.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

A. Ahmad Bakir (Conceptualization; Visualisation; Writing – original draft)

M. J. Mohamed Mokhtarudin (Methodology; Formal Analysis; Resources)

N. H. Johari (Writing – proof-read; Supervision)

AVAILABILITY OF DATA AND MATERIALS

The datasets used and/or analysed during the current study, including the 3D CAD models and mechanical testing data, are available from the corresponding author on reasonable request.

ETHICAL STATEMENT

This research did not involve human participants, animals, or sensitive data. Therefore, ethical approval and informed consent were not required.

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