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Improvements of the Bandwidth and Radiation Characteristics of a 5G Mobile Communications Microstrip Antenna with a Novel Wedge Shaped Substrate Design

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***Abstract**: This study proposes a new approach for designing microstrip antennas. The resonant frequency of the proposed antenna is 3.55 GHz, allowing it to operate in the current 5G band (mid-band). The design approach is based on a wedge-shaped substrate with a relatively low thickness at the level of the feed line and a higher thickness at the level of the radiating patch. The FR4 wedge substrate-based design of a 6 mm linear slope enhances the radiation by 9% and the bandwidth by 10.3%, while degrading the return loss by 2.3 dB compared to a standard box substrate-based antenna design of the exact dimensions. To remedy the degradation in terms of S11, the rectangular inset feed line is replaced by a trapezoidal one, which re-enhances the return loss by 3.4 dB, making it better than the original one.*

***Keywords:** Bandwidth, Directivity, Inset Fed, Microstrip Antenna, Wedge Substrate, 5G Mobile Communication.*

I. INTRODUCTION

With the arrival of smartphones on the market sixteen years ago, the demand for significant and high-rate data traffic has continued to increase year after year. Before the era of smartphones, users had only the option of exchanging short messages, in addition to making audio calls. Internet access via smartphones triggered the demand for data-intensive content, starting with video streaming and extending to IoT applications. The insatiable appetite for data-intensive content, associated with the exponential growth in the number of users, prompts mobile network operators to request that network developers continually enhance the performance of their deployed networks. This is how the mobile network has undergone five major upgrades since its inception to reach 5 5G. The key element that allows increasing the number of users while providing each of them with more data traffic and higher throughput is to increase the number of frequency channels by spacing them out as much as possible. This leads developers to change the band of use in the frequency spectrum each time, moving towards higher and higher frequencies.

Three frequency bands are utilised in a 5G system. The first one is the 700 MHz band (694 MHz-790 MHz). The second one is the 3.6 GHz band (3400 MHz-3800 MHz). The third one is the 28 GHz band (27.5 GHz – 28.35 GHz) [1], [2]. The second band constitute the cornerstone of the 5G system because it provides a good compromise between relatively low attenuation signal propagation and high spectral resources capacity [3].

Following the choice of this spectrum, it becomes necessary to adapt the elements of the communications network infrastructure to operate in this new band while keeping the performance criteria at a certain minimum acceptable level or even improving them, especially in terms of bandwidth and directivity. The most crucial network key element which needs to be rethought is the antenna.

In general, PCB antennas have the advantage of being easily accommodated within the device package. Additionally, they are very economical and easy to manufacture. Microstrip antennas are the most popular form of PCB antennas because they are lightweight, compact in size, low in cost, and integrable with integrated circuits. At the same time, they have some drawbacks like the low gain and the narrow bandwidth [4], [5].

Having coplanar radiation elements and power supply, the microstrip patch antennas (MPAs) make it possible to establish a balance between manufacturing complexity on the one hand and good performance on the other hand [6]. However, MPA antennas pose a serious and critical problem because they have a high antenna quality factor (Q). Unfortunately, high Q leads to a narrow bandwidth and low efficiency, which makes their use in a broadband system such as the 5G systems inappropriate [7]. The primary objective of this work is to address the narrow bandwidth limitation of MPA by incorporating a new element into the antenna design while maintaining the operational functionality of the other design elements. In this way, it will allow for a net improvement in bandwidth and antenna gain, regardless of all other design elements.

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Thus, the combination of the proposed technique with other techniques enables the achievement of even better characteristics.

In high frequency, the dependence of the antenna performance criteria, such as directivity and bandwidth, on the dielectric substrate and other electrical parameters becomes much more sensitive than in low frequency [8].

All academic and industrial studies conducted to date on the design of microstrip patch antennas have proposed designs based on the exploration of all possible geometric shapes of the antenna's radiating part. These shapes vary from rectangular to circular through Cross, Z, U, V and even Seljuk star shapes [9]-[14]. Several other studies have explored the effects of varying the antenna dimension elements on performance criteria. For example, [6],[15],[16] explored the effect of varying substrate thickness and patch width on the antenna bandwidth and gain.

This study presents a new approach for the design of MPA. The key element of this approach is the use of a wedge-shaped substrate instead of a box-shaped one. While [17] proposed only a theoretical calculation of the resonant frequency of a rectangular patch antenna mounted on a wedge-substrate without a feed line; this study presents a practical wedge-substrate antenna equipped with a feed line. It demonstrates the enhancement of all antenna performance criteria, especially in terms of bandwidth, except for return loss, compared to the same patch antenna when constructed on a conventional box substrate. The study concludes by proposing a new design for the feed line of the wedge-substrate antenna that corrects the degradation of the return loss, yielding a result that is even better than the wedge-substrate design and the standard prevalent box-substrate design.

Wedge-shaped microstrip antenna

A practical microstrip antenna is composed mainly of two parts: the radiating patch and the microstrip feed line, which relates the input connector to the radiation element. Of course, these two parts are etched on a dielectric substrate, separating them from the ground plane of the antenna.

Because the feed line is straight, it will not radiate. The reason radiation is prevented in this type of line is its symmetry, which allows the fringing fields along the line to be balanced, thereby obtaining the cancellation of any radiated energy. This is not the case with the patch due to its discontinuity at the ends. Microstrip antennas are characterised by an electric field equal to zero at the centre of the patch. On the other hand, at the edges of the patch, an electric field is radiated. This radiation is due to the excessive fringing field between the edge of the patch and the ground plane. The magnitude of the fringing field is a function of the dimensions of the patch and is at the same time proportional to the thickness of the substrate [18].

Accordingly, the radiation is directly proportional to the thickness of the substrate. Thus, a high thickness at the patch level is preferred to improve radiation and enhance the antenna's gain. However, a lower thickness at the level of the feed line is desirable to minimise radiation losses. While a standard box substrate antenna does not offer this combination because the thickness is uniform throughout the device, it becomes possible to combine a low-thickness transmission line with a high-thickness patch antenna if a wedge-shaped substrate is used. The radiation is not the only characteristic that depends on the thickness. Another important antenna characteristic is directly related to the thickness. It is the bandwidth of the antenna, as demonstrated in the next section. Figure 1 presents a conceptual geometry of a wedge-shaped patch antenna. This study will demonstrate the enhancement of bandwidth and radiation, in addition to other performance parameters, with the use of this concept approach by comparing the performance criteria of two antennas. The two antennas will have the same upper layer geometry; however, the first will be mounted on a rectangular box substrate, and the second will be mounted on a wedge substrate.

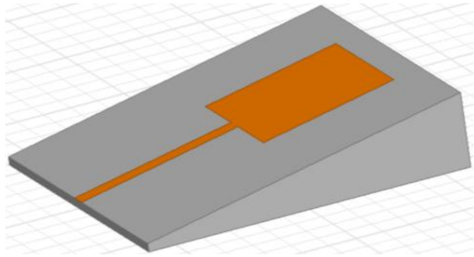

Fig.1. Geometry of a Wedge-Shaped Patch Antenna

II. CIRCUIT DESIGN

The dimensions of MPA depend on several variables, primarily the resonance frequency, as well as the thickness and permittivity of the dielectric layer. As mentioned earlier, the antenna in this study is designed to operate at a centre frequency of 3.55 GHz. The substrate used is FR4, having a relative dielectric permittivity of 4.4.

Because the substrate thickness of the proposed design will be variable, it is essential to determine the allowable range of variation of this parameter before conducting any other design calculations. The upper value of the thickness can be determined from the following relationship [19], [20].

$$h \leq \frac{0.3c}{2\pi f\sqrt{\varepsilon_r}} \tag{1}$$

In the previous equation, the variable c is the speed of light, and f is the resonance frequency. ε_r Is the relative permittivity of the substrate, and h is the thickness. For the chosen frequency and permittivity, h must not exceed 1.95 mm.

While the thickness h of a FR4 standard box substrate is 1.6 mm, h here varies from h1=1.5 mm to h2 = 2.1 mm between the two edges of the substrate wedge of 60 mm in length. In this way, the upper edge of the patch has a thickness h of 1.9 mm. Note that the width of the substrate wedge is also 60 mm. Accordingly, and as shown in Figure 2, the height (z) of the substrate varies as a function of the depth (y) with the following equation:

$$z = 0.01y + 1.8 \tag{2}$$

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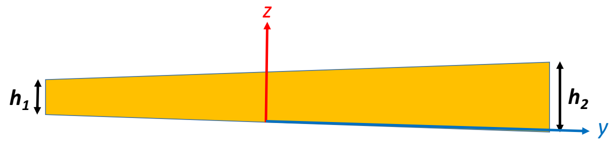

Fig. 2. Side view of the Wedge-Shaped Substrate Used in this Study

The width of the radiating element is determined based on the following relationship, where c is the light velocity, f_r Is the resonance frequency and ε_r Is the relative permittivity[21, 22]:

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{3}$$

Then the effective length of the patch is determined based on the following equation [23, 24]:

$$L_e = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} \tag{4}$$

Where the following relationship defines the effective relative permittivity [25, 26]:

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2\sqrt{1+12\frac{h}{W}}} \tag{5}$$

Ultimately, the length of the patch is optimised based on the following relationship.

$$L = L_e - 2\Delta L \tag{6}$$

Where [27, 28] $\Delta L = \frac{0.412h(\varepsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{W}{h}+0.8)}$ (7)

The length L and width W of the patch element are calculated to be 20 mm and 26 mm, respectively. For these dimensions of the patch, its edge impedance is 264 Ohms.

The patch is related to the port of excitation via a microstrip transmission line, as shown in Fig. 3. To obtain a 50 Ω transmission line, the width of this line, w0, is calculated to be 3.08 mm. Note that here the line is not simply connected to the patch due to the mismatch between the line impedance and the patch edge impedance. The technique of Inset feed line is used in this design as an alternative to allow the line to meet the patch at a depth where the impedance of the patch is equal to the impedance of the line—the input impedance decreases as we move from the edge of the patch to its centre. Figure 3 shows a top view of the patch antenna with its feed line.

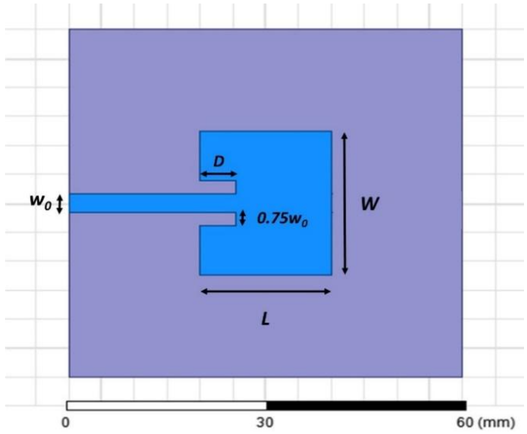

Fig. 3. Top View of the Wedge-Shaped Substrate Square Patch Antenna

The necessary depth, D, in the patch to obtain a 50 Ω impedance is calculated to be 5.4 mm. The notch width, which is the spacing between the line and the patch, is also estimated to be 0.75 w_0.

III. RESULTS AND DISCUSSION

Before presenting the simulation results, a theoretical determination of the bandwidth as a function of substrate thickness is necessary to serve as a reference for the simulations. Based on the dimensions of the proposed antenna and using the following relationship [29]:

$$BW = 3.771\left[\frac{\varepsilon_r-1}{(\varepsilon_r)^2}\right]\cdot\frac{h}{\lambda_0}\cdot\left(\frac{W}{L}\right) \tag{8}$$

The theoretical bandwidth for the proposed design is approximately 11% for a substrate thickness of 1.6 mm and approximately 13% for a thickness of 1.9 mm. Note that λ_0 In the previous equation, λ is the wavelength.

The design presented in the previous section is simulated in the electromagnetic radiation software HFSS. Figure 4 shows an overview of the designed antenna.

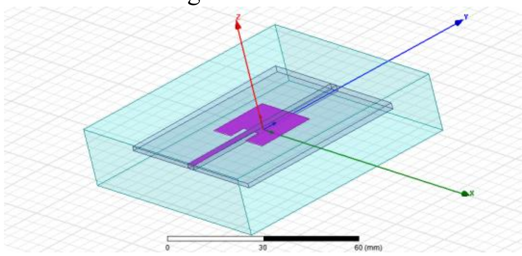

Fig. 4. Wedge-shaped Substrate Square Patch Antenna Design

In this section, the simulation results, in terms of return loss, bandwidth, and gain, of this design will be compared to those of a standard box substrate design of the exact dimensions. Figure 5 shows a superposition of the variation in return loss for both designs between 2.5 GHz and 4.5 GHz. The simulated resonant frequency of the box-based design is 3.55 GHz, with a minimum return loss of -23.05 dB, and the -10 dB bandwidth is 109.5 MHz. On the other hand, the simulated resonant frequency of the wedge-based design is 3.53 GHz, with a minimum return loss of -20.76 dB, and the -10 dB bandwidth is 114.1 MHz.

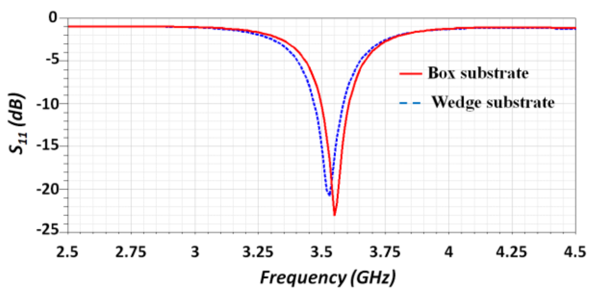

Fig. 5. Simulated Bandwidth and Return Loss for Box and Wedge Substrate Designs

Figure 6 shows a superposition of the variation of the antenna gain as a function of the angle θ. The maximum gain is obtained for θ = 0, and this is true for both designs. The maximum gain for the box-based design is 1.9009, while the maximum gain for the wedge-based design is 2.067.

To summarise, the wedge-based design presents an enhancement of 4.2% in terms of bandwidth and an enhancement of 8.74% in terms of radiation gain. These enhancements are obtained at the expense of the return loss, resulting in a 2.3 dB loss in the wedge-based design compared to the standard box-based design.

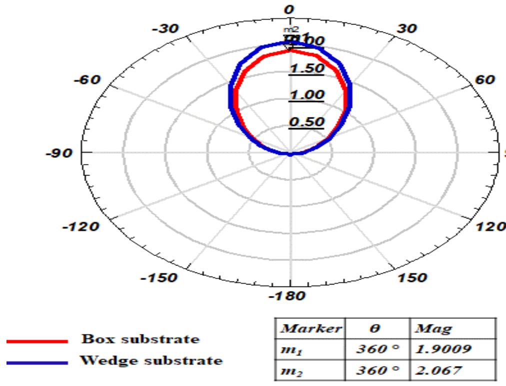

Fig. 6. Simulated Radiation Pattern for Box and Wedge Designs

IV. TRAPEZIUM INSET FEED LINE

The characteristic impedance Z_0 of a microstrip line is inversely proportional to the ratio W/H, where W is the width of the line and H is the height or thickness of the substrate. According to Bahl and Trivedi [30], the expression of the characteristic impedance Z_0 of a microstrip line when W/H > 1 is :

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_e}\left(\frac{W}{H}+1.393+\frac{2}{3}\ln\left(\frac{W}{H}+1.444\right)\right)} \tag{9}$$

Where $\varepsilon_e = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+12\left(\frac{H}{W}\right)\right)^{\frac{-1}{2}}$ (10)

The above equations demonstrate that a change in height, which corresponds to a change in the thickness of a microstrip line, alters the characteristic impedance of the line, thereby affecting the return loss or reflection coefficient of the line. That is why, to make the thickness variable while not affecting the characteristic impedance, the width of this line must change with the same linear slope as the thickness, and in this way, the fraction W/H remains constant. This principle forms the basis of the solution proposed in this section, which aims to correct the degradation of the wedge-based design in terms of return loss. Thus, the rectangular feed line of the previous section is replaced this time by a trapezoidal one, as shown in Figure 7. Calculations are made to maintain an impedance of 50 Ω along the entire length of the line. For this design, the width of the line starts at w0S = 2.89 mm at the port level and ends at w0L = 3.38 mm at the intersection level with the patch.

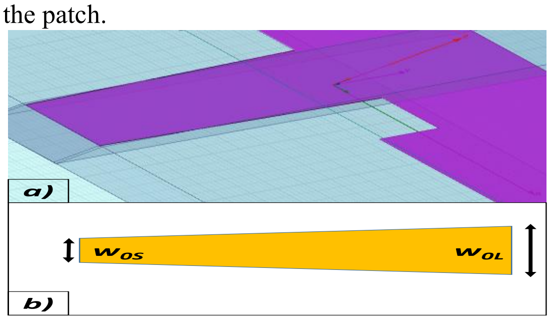

Fig.7. Modification in the Inset Feed Line: (A) Overview of the New Hfss Model, (B) New Trapezium Feed Line Dimensions

Figure 8 illustrates the significant improvement in return loss achieved using this technique, with a minimum simulated return loss of -24.12 dB at a resonant frequency of 3.54 GHz. The -10 dB bandwidth with this technique is 120.8 MHz. Figure 9 shows a superposition of the variation of the antenna gain as a function of the angle θ for both designs. The maximum gain for the wedge-based design this time is 2.0735. To summarise, the design with a trapezoidal feed line associated with a wedge substrate presents an enhancement of 10.3% in terms of bandwidth, which is very close to the theoretical result presented at the beginning of the previous section, and an enhancement of 9.07% in terms of radiation gain. At the same time, the return loss is not degraded. On the contrary, it is much better.

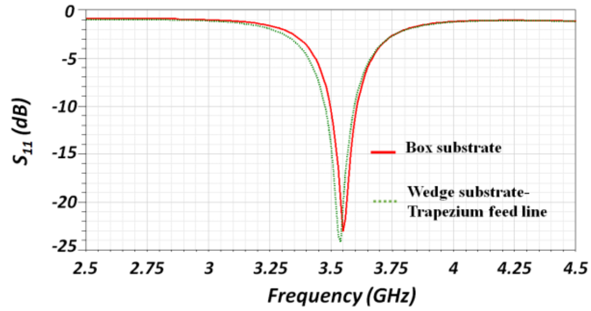

Fig. 8. Simulated Bandwidth and Return Loss for Box and Wedge-Substrate-Trapezium Feed Line Designs

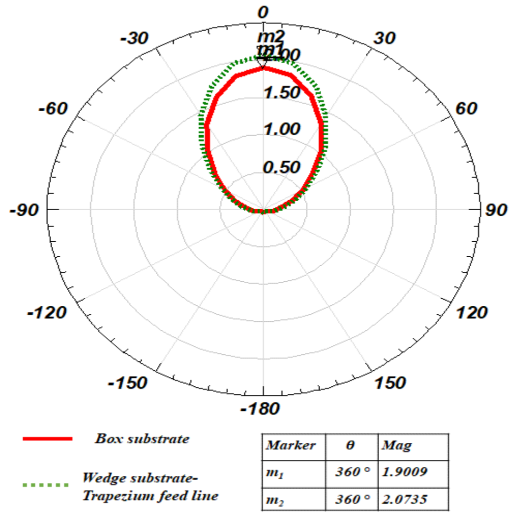

Fig. 9. Simulated Radiation Pattern for Box and Wedge-Substrate-Trapezium Feed Line Designs

Figure 10 shows that the radiation beam width is the same in both versions of the antenna: the box substrate-based one and the wedge substrate-based one. Both have a standard microstrip antenna angular width of 84° in the E plane. This means that the beam width of the proposed wedge-based antenna remains unaffected, despite the significant modification to the elevation angle due to its design nature. Figure 11 shows the three-dimensional radiation pattern of the proposed antenna.

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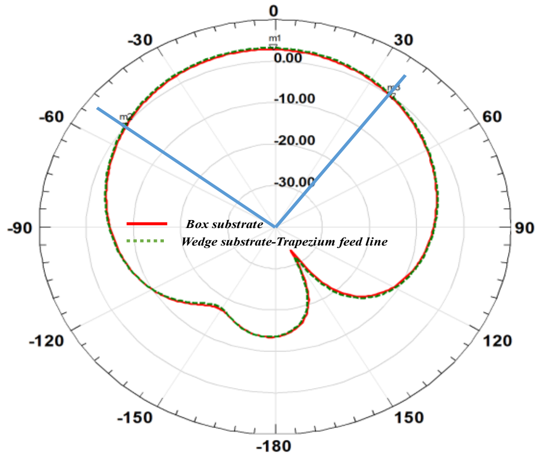

Fig. 10. Simulated 3 dB Angular Width for Box and Wedge-Substrate-Trapezium Feed Lin Designs.

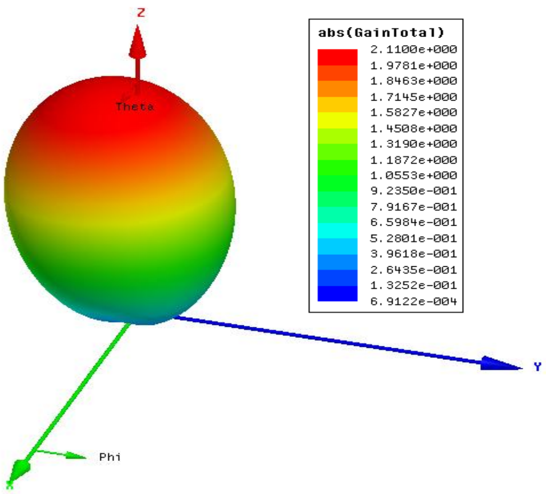

Fig. 11. The three-dimensional (3D) View Of the Radiation Pattern For The Proposed 5g Antenna Model

Figure 12 shows the current distribution of both antennas. The current should be minimal at the edges of the antenna, with a maximum voltage, and this is reproduced at the middle of the wave at the level of the feed line. It can be observed that the current distribution is almost identical in both antennas, indicating that the current distribution is not significantly affected by the symmetry modification in the proposed wedge-based antenna.

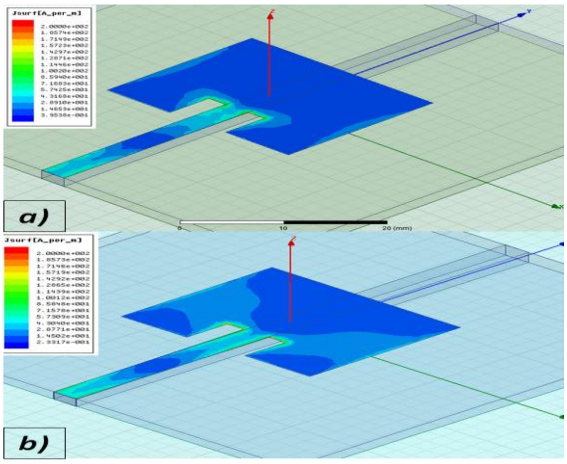

Fig. 12. Simulated Current Distribution for (a): box and (b): Wedge-Substrate-Trapezium Feed Line Designs

V. CONCLUSION

This paper presents a new design approach for microstrip antennas. In this design, the standard box substrate is replaced by a wedge-shaped substrate associated with a trapezoidal feed line, rather than a rectangular one. The results obtained in terms of return loss, bandwidth and radiation gain are auspicious and validate the approach. The FR4 wedge substrate-based proposed design, with a 6 mm linear thickness slope, enhances the radiation by 9% and the bandwidth by 10.3%, while maintaining the return loss comparable to that of a standard box substrate-based antenna design of the exact dimensions. These results are encouraging and can serve as a basis for further investigation or even an attempt at realisation and measurement. Ultimately, the design approach presented in this study is entirely new, which prevents its comparison with similar works. At the same time, this design approach is fully combinable with other design approaches, such as new MPA planar geometries, to obtain better results.

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Ethical Approval and Consent to Participate	No, the article does not require ethical approval or consent to participate, as it presents evidence that is already publicly available.
Availability of Data and Materials	Not relevant.
Authors Contributions	All authors have equal participation in this article.

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