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Microstrip Antenna for Radar-Based Microwave Imaging of Breast Cancer: Simulation Analysis

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Abstract – *The paper proposes a radar-based microwave imaging system for breast cancer detection by using a simple and effective design of a wideband microstrip patch antenna. Breast cancer is the second-highest cause of death among women worldwide and the only way to provide an effective treatment is to detect it at an early stage. Microwave imaging (MI) provides a safer and cheaper detection method as it uses low-level non-ionizing radiation. A compact wideband microstrip patch antenna working in the frequency range of 3.6 to 9.2 GHz frequency is used for the MI system. The antenna has a minimum return loss of -48 dB and a maximum gain of 4.5 dBi. Antenna is scanned over the breast tissue and a significant contrast in the reflected signals in the presence of the tumor is reported. The reflected signals at different positions of the antenna are then used to create a 2D image of the breast tissue showing the position of the tumor inside it. Specific absorption rate is also calculated in the tissue and is found well below the safety levels.*

***Keywords**: Breast Cancer Detection, Microstrip Patch Antenna, Microwave Imaging, SAR, MATLAB, COMSOL Multiphysics, 2D Representation*

Nomenclature

S11	Antenna reflection coefficient
ε_r	Dielectric constant
σ	Electric conductivity
ρ	Tissue density
E	Electric field intensity
f_r	Resonance frequency
FR4	Flame retardant 4
MI	Microwave Imaging
CST	Computer Simulation Technology
SAR	Specific Absorption Rate

I. Introduction

World health organization has stated breast cancer to be a major cause of death in women worldwide.

According to a report in 2018, approximately 627,000 women died because of breast cancer, which makes 15% of all sort of cancer deaths in that year [1]. Breast cancer happens due to an unwanted development of malignant or cancerous cells in the breasts. The first and foremost step in providing a rapid and successful treatment in breast cancer requires early stage detection. Most popular techniques involved in breast cancer detection are X-ray mammography, ultrasound, Magnetic Resonance Imaging (MRI), and Computed Tomography (CT scan).

However, all these techniques suffer from some serious shortfalls, which affect their performances adversely. X-ray mammography uses ionizing radiations, which could damage the healthy tissues, leaving the patient's life at higher risk. Moreover, it is uncomfortable and painful for some women as it requires the breast to be pressed in between the mammography equipment. Going through this much danger and pain, X-ray mammography still has shown false-negative and false-positive results more than 30% of the times. It cannot detect small size tumors nor it can process dense breast tissues which mostly are found in younger women. CT scan as well uses ionizing radiation and is mostly used to do the diagnosis in larger vessels. Ultrasound and MRI uses non-ionizing radiation making them a lot safer than X-ray mammography and CT scan. However, these techniques cannot detect tumor at early stages and are mostly used in the latter part of the screening to distinguish between the cancerous and non-cancerous tumors [2], [3]. Even if used altogether, the techniques do not comply with the requirement of the U.S. Institute of Medicine reported in [4]. With such limitations in the technologies, the researchers have kept looking for better alternative that could make the breast tumor detection safer and cheaper without compromising with the performance. Microwave imaging (MI) is the one that has attracted research interest recently. MI is a non-ionizing, non-invasive, and an inexpensive technique. It has been studied and used in the medical field for over 40 years. Bolomey [5], presented a thorough history of MI and it's comparison with the current available techniques in the biomedical field. In breast cancer detection MI has shown positive results in detecting the small size tumors that too at an early stage. MI uses microwave radiation which falls under the frequency range of 300 MHz to 300 GHz. This frequency range offers good penetration depth in the tissues without causing any adverse effect on the patient's health. Moreover, MI does not require any breast compression making it a comfortable technique for women. Even with such advantages, there are not enough microwave-based breast imaging systems [6]-[8].

Researchers have been using different types of antennas for MI of breast cancer. The breast is scanned with the antenna, the scattering parameters (S11) of the reflected waves are collected and used to generate a complete picture of the breast out of it. Wideband antennas working between the frequency range of 3 to 10 GHz have been preferred for MI as they provide better spatial resolution and good penetration depth. key point in MI for breast cancer is the difference found in the dielectric properties of the healthy and cancerous tissues at microwave frequencies. The dielectric properties of cancerous tumor are higher than the rest of the breast tissues. A significant difference in the reflection coefficient of the antenna can be seen when the microwaves suddenly irradiate the tumor area which differs a lot in dielectric properties from the normal tissue. These differences in the reflected signals are used in finding out the position of the tumor. MI can be classified into two categories: tomography and radar-based. In tomography, the EM signals are incident on the breast and the electric profile of the whole breast is created by using an ill-posed scattering approach.

However, this whole process is complex and a little time consuming [9], [10]. In radar-based MI, the breast is irradiated from several points and the scattered signals are collected. These scattered signals show contrast between the normal and cancerous breast. This contrast in the scattered signals from the normal and cancerous breast is used to identify the position of the tumor inside the breast [11], [12]. Radar-based MI can further be classified into three categories: monostatic, bi-static, and multi-static. The monostatic MI system requires only single antenna for scanning the breast. The antenna works both as a transmitter and receiver. In bi-static MI system, two antennas are used to scan the breast, one working as a transmitter and another as receiver. And lastly, in a multi-static MI system, more than two antennas or an array of antennas are used to scan the breast. The breast is covered by the multiple antennas one working as a transmitter at one time while rest of them working as receivers. The multi-static MI is known to provide better results. However, using multiple antennas makes the MI system expensive. Microstrip patch antennas have been preferred lately due to its low cost, easy fabrication, and ease of accessibility. However, they suffer from narrow band width. Many techniques have been opted by the researchers in order to make these antennas wide band and suitable for MI [11], [13], [14].

Klemm et. al [15] designed 16 stacked patch antennas. They also presented a real time MI system for breast cancer detection for the first time ever. The experiment was performed by using the array of 16 UWB stacked patch antennas in hemispherical shape. A breast phantom was used and the results were obtained without any mechanical moment. Kaur et. al [2] designed a three layered stacked patch antenna. The antenna had total 6 layers. Second, Fourth, and Sixth layers were substrate.

First layer was a parasitic patch having a U-shaped slot. Third was a swastika shaped active patch. Fifth layer was ground plane with "+" shaped DGS. And last seventh layer was a rectangular shaped feed line. The antenna was performing a monostatic imaging where it was scanned over a breast phantom having two sizes of tumors. The detection of tumors was performed by using the 'S' parameter technique. Hossain et al. [16], [17] made a microwave imaging system of 16 array of slotted patch antennas. The antennas were compact in size and slotted with circular and trapezoidal shapes in patch and ground side. A breast phantom was scanned with the antenna array system and the tumor detection was successfully performed. They also designed a patch antenna having a diamond shaped patch with three octagonal shaped parasitic resonators on it. The ground plane was partial having rectangular shaped slotting.

Adding this parasitic resonator have significantly increased the directivity, bandwidth, and gain of the antenna making it more suitable for MI system. In this paper, a low cost and very simple design of a wideband microstrip patch antenna without using any complicated methods (such as an extra layer of substrate [2], [18], EBG [19], etc.) is designed and used in MI system for breast cancer detection. The antenna is compact in size having the dimension 25 mm×30 mm×0.794 mm.

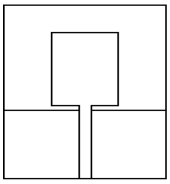
Slotting has been performed in the ground and patch of the antenna in order to increase its bandwidth and the imaging quality [20]. The gain, and radiation pattern of the antenna have also been studied. Three rectangular boxes are made and used as the skin, fat, and tumor of the breast. The antenna is scanned over the breast model and the scattering parameters (S11) for with and without tumor are collected. The paper presents a MI system using only one antenna (monostatic imaging) making it a very cost-effective system in comparison to the multi-static ones [21]. The proposed antenna is able to detect the embedded tumor inside the breast tissue by maintaining the Specific Absorption Rate (SAR) value below the safety levels.

The rest of the paper is organized as follows. Section II presents the problem formulation describing the steps involved in the designing of the antenna and breast model, scanning procedure used for the microwave imaging, and the parametric sweep performed on the antenna. Section III discusses the results such as SAR calculation in the breast model, gain and radiation pattern of the antenna, detection of the tumor as a result from the scanning. Finally, Section IV concludes the results and the findings.

II. Problem Formulation

II.1. Antenna Designing

A wideband microstrip patch antenna [26]-[29] is designed on a FR4 substrate of dielectric constant ε_r = 3.34 and thickness h=0.794 mm. The antenna was designed for a resonance frequency f_r = 7 GHz [22]. To make it wideband, the antenna is then modified by making the ground plane shorter and adding slots in the patch and ground. Step by step progression of the antenna is shown in Figs. 1. The slots made in the ground and patch have been found to significantly improve the S11 signals of the antenna (Fig. 2). From the final version of the antenna, a minimum value of -48 dB S11 and a bandwidth of 87.5% is achieved [23]. Figs. 3 show the final simulated design of the proposed antenna and Table I shows all the dimension for it.



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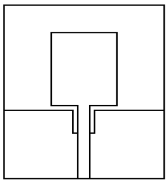

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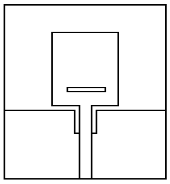

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Figs. 1. Step by step design of the antenna

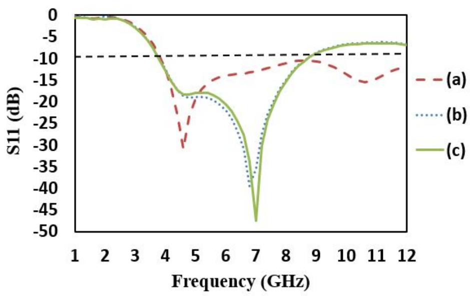
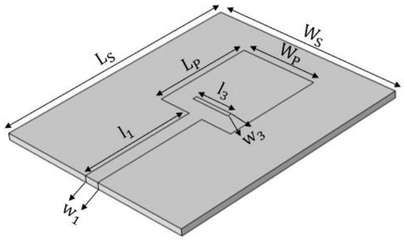


Fig. 2. Reflection coefficients (S11) of all three antenna designs

TABLE I
DIMENSIONS OF THE PROPOSED ANTENNA

Parameter	Dimension (mm)
L_s	30
W_s	25
L_p	12
W_p	10
L_g	13.2
l_1	14
w_1	1.8
l_2	3
w_2	2.5
l_3	5
w_3	0.5



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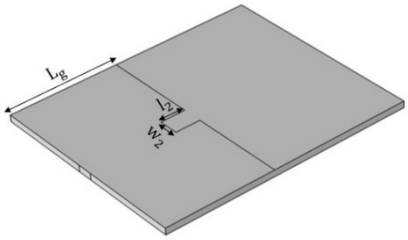


(b)

Figs. 3. Proposed antenna: (a) front and (b) back

II.2. Breast Tissue Modelling and Scanning Procedure for Microwave Imaging System

Fig. 4 shows a 3-D image of the breast model used for testing the antenna's capability of detecting the tumor.

The dimensions of the breast model and the tumor are shown in Table II.

Antenna scans over the breast tissue while keeping a distance of d = 6.2 mm from the tumor. Dielectric properties assigned to the breast tissue and tumor are mentioned in Table III, where σ is the conductivity (S/m) and ε_r is the permittivity of the tissue.

The antenna scans over the breast in y-direction for a total of 77 positions, shown in Fig. 5. The scanning procedure is performed in two sets 1) when tumor is present in the breast and 2) when tumor is absent in the breast. The reflection coefficients for both the sets at all positions are collected and used to find out the positions of the tumor.

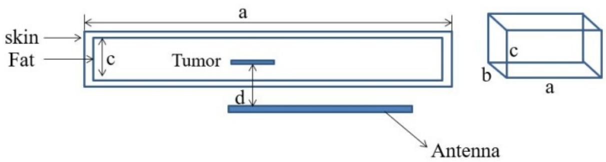


Fig. 4. Model of the breast tissue used in the study

TABLE II
DIMENSIONS OF THE BREAST MODEL

Parameter	a	b	c
Skin	50 mm	40 mm	10 mm
Fat	45 mm	35 mm	9 mm
Tumor	8 mm	8 mm	2.4 mm

TABLE III
DIELECTRIC PROPERTIES OF TISSUES [3]

Parameter	Conductivity σ(S/m)	Permittivity ε_r
Skin	1.49	37.9
Fat	0.14	5.14
Tumor	1.20	50

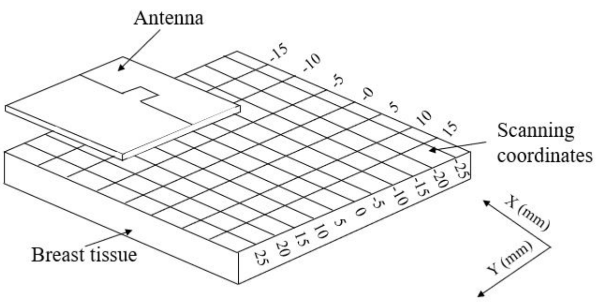


Fig. 5. Scanning coordinates for MI system

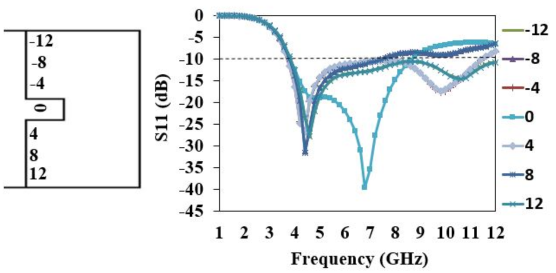
II.3. Parametric Study of Antenna

Parametric study is conducted to see the impact of the slot's positions on the antenna's performance. The position of the ground and patch slots are varied to get a good impedance matching. The ground slot is moved in the steps of 4 mm while the patch slot is moved in the steps of 1.6 mm ranging from -12 to 12 mm and -9.6 to 0 mm, respectively. The effect of the slot's position on the S11 are shown in Figs. 6(a) and (b). As can be seen, when the slots are at position "0" for both ground and patch, the S11 gives broader bandwidth compared to any other positions. All other slot positions give S11 nearer to -10dB. Hence, the ground and the patch slots at positions "0" are chosen for the antenna.

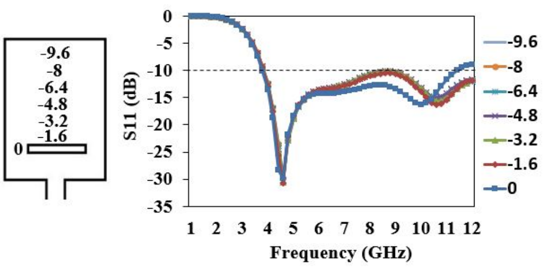
III. Results and Discussions

III.1. SAR Calculation

The antenna is checked for whether the maximum SAR value generated in the exposed tissue is below the safety levels.



(a)



(b)

Figs. 6. S11 curves for different positions of slots on (a) ground and (b) patch

SAR is power dissipation rate normalized by the material density and can be described by the following formula:

$$SAR = (\sigma/\rho)|\bar{E}| \quad [\mathrm{W/kg}] \tag{1}$$

where σ is electric conductivity (S/m), ρ is the tissue density (kg/m^3) and $\bar{E}$ is the electric field intensity (V/m).

Fig. 7 depicts the image of the antenna scanning the breast tissue at one point in the simulation. The SAR value calculated in the skin layer of the breast tissue is 0.97 W/kg which is well below the restricted value of 1.6 W/kg established by the International Corporation of Non-ionizing Radiation Protection (ICNIRP) [24].

Hence, the proposed antenna is safe to be used in MI system.

III.2. S11 Comparison Between Simulated Antennas

In MI system, the S11 value of the antenna has to be minimum so that the maximum power of the antenna radiates out, which provides better chances of tumor detection. The designed antenna gives a minimum value of S11 -48 dB at 7GHz frequency. COMSOL Multiphysics software is used for designing the antenna and the obtained return loss in it is then compared with the CST software (Fig. 8). As can be seen, the proposed antenna's S11 shows good results with the CST software, which validate the design.

III.3. Gain and Radiation Pattern of Antenna

A graph between the antenna's frequency range and gain is depicted in Fig. 9(a). The antenna achieves a maximum gain of 4.5 dBi at 11 GHz frequency. Fig. 9(b) shows the 3D radiation pattern of the maximum gain (2.51 dBi) for 7 GHz frequency.

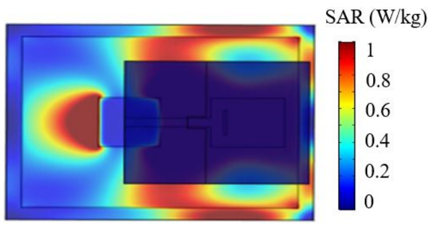


Fig. 7. SAR calculation in the breast tissue due to exposure from the proposed antenna

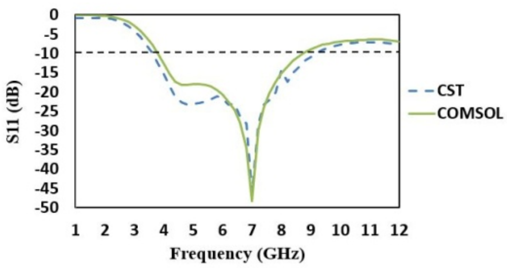
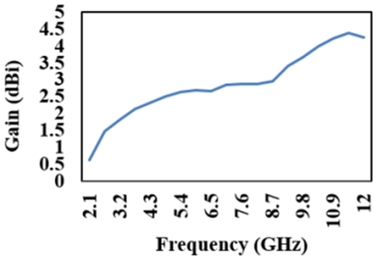
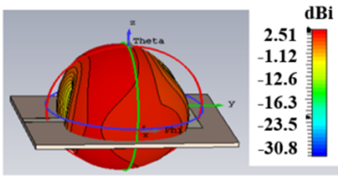


Fig. 8. Comparison of the simulated reflection coefficients (S11) of the antenna



(a)



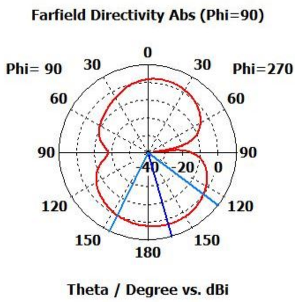
(b)

Figs. 9. Gain of the proposed antenna (a) gain vs. frequency graph, (b) 3D radiation pattern of gain at 7 GHz

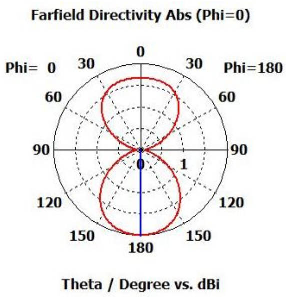
The 2D radiation patterns of H-plane (x-y plane) and E-plane (x-z plane) for 7GHz frequency are shown in Figs. 10 (a) and (b), respectively. The E and H-plane give more detail about the radiation behavior of the antenna.

III.4. Comparison Between the Performance Analysis of the Proposed Antenna with the Literature

The characteristics of the proposed antenna such as its dimension, bandwidth, and S11 value are compared with the existing antennas, shown in Table IV. The proposed antenna's compact size makes it handy and more suitable to be used in the MI system. The wider bandwidth helps in better detection of the tumor.



(a)



(b)

Figs. 10. 2D radiation pattern of the antenna at 7 GHz (a) H-plane, (b) E-plane

TABLE IV
COMPARISON OF THE PROPOSED ANTENNA WITH THE LITERATURE

References	Dimensions (mm^3)	Frequency range (GHz)	Return loss (S11)
Proposed Antenna	25×30×0.794	3.6-9.2 (87.5%)	-48 dB
[13]	34×36×1.6	4.6-9.6 (70%)	-25 dB
[14]	50×30×1.57	4.8-6.1 (23.8%)	-45 dB
[11]	34×36×1.6	2.4-4.7 (64.78%)	-30 dB
[25]	NR	6.4-10 (44%)	-22 dB
[2]	37×43×4.85	4.9-10.9 (75.94%)	-30 dB

Whereas, the low S11 gives a clearer image as most of the power of the antenna is radiated out and experiences less reflection in irradiating the tumor.

III.5. S11 Signal from Scanning

The proposed antenna is used in the MI system for detecting the tumor embedded in the breast tissue. Fig. 5 Shows the scanning coordinates at which the antenna is moved above the breast tissue. The S11 signals for all 77 positions are recorded first in the presence and then again in the absence of the tumor. It was observed that the presence of the tumor gives very low value of reflection coefficient. Fig. 11 shows the maximum difference in the S11 signals in the presence and absence of the tumor.

The antenna is placed at x=0 and y=0 coordinates above the breast tissue. S11 signals for all coordinate positions are then recorded and used to create a 2D image out of it.

III.6. Detection of Tumor

The antenna is scanned at 77 positions above the breast tissue in the presence of the tumor. S11 (dB) signals at each position of the antenna are collected and stored in a matrix form of 7×11 size, shown in Fig. 12.

The encircled part in the middle of the image shows the position of the tumor in the breast. Reflection coefficients obtained at all positions of the antenna during the scanning are shown in Table V. As can be seen, the minimum value of reflection coefficient i.e. -38 dB is found at the x=0 and y=0 coordinates. This is the place where the tumor is just below the antenna inside the breast. As soon as the antenna goes away from this position, the value of the reflection coefficient becomes stable. No major difference in the reflection coefficients can be seen at other places of the breast except the one where the tumor is embedded.

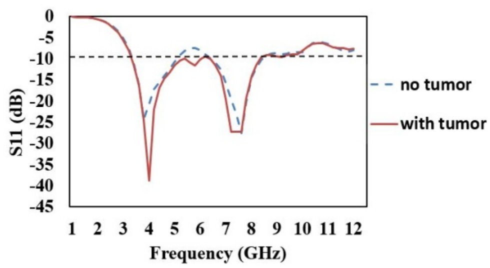


Fig. 11. Reflection coefficient of the antenna in presence and absence of the tumor

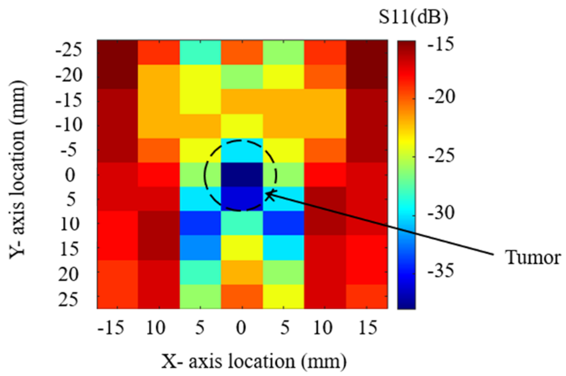


Fig. 12. Contour image of the breast showing the position of the embedded tumor in it

TABLE V
REFLECTION COEFFICIENT VALUE AFTER SCANNING THE BREAST TISSUE

-25	-15	-19	-28	-20	-28	-19	-15
-20	-15	-20	-24	-26	-24	-20	-15
-15	-16	-22	-22	-22	-22	-22	-16
-10	-16	-22	-22	-24	-22	-22	-16
-5	-16	-20	-24	-30	-24	-20	-16
0	-17	-18	-26	**-38**	-26	-18	-17
5	-17	-18	-30	-36	-28	-16	-17
10	-18	-16	-34	-28	-32	-16	-17
15	-18	-16	-30	-24	-30	-17	-18
20	-18	-17	-28	-22	-26	-17	-18
25	-19	-17	-26	-20	-24	-18	-19
Y / X	-15	-10	-5	0	5	10	15

IV. Conclusion

The paper focuses on developing a simple and effective MI system for breast cancer detection. A compact wideband microstrip patch antenna with dimensions 25mm×30mm×0.794mm is designed to be used in a monostatic imaging of breast cancer, making the system cost effective, portable, and safer. The antenna has a return loss value below -10 dB for the frequency range of 3.6 to 9.2 GHz. A minimum return loss value of -48dB at 7GHz and a maximum gain of 4.5 dBi at 11 GHz is reported in free space. The antenna is scanned over the breast tissue and a significant contrast in the reflection coefficients (S11) can be seen in the presence of the tumor. All the reflection coefficients are then collected and placed in a matrix form to create a 2D contour image of the breast showing the position of the tumor in it. In future the results will be validated with an experimental setup of MI. The antenna will be designed and scanned over a breast phantom. More layers of breast could also be added in order to make the system more complicated and realistic.

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