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ELECTROMAGNETIC WAVE INTERACTION WITH BREAST TISSUE USING MICROWAVE IMAGING WITH ULTRA-WIDEBAND ANTENNAS

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ABSTRACT

Contemporary microwave imaging represents a compelling methodology for identifying malignant formations within the anatomical structures of the breast by leveraging electromagnetic propagation. When radio frequency energy couples with biological tissues through an antenna, the resultant interactions demonstrate substantial clinical potential. This study examines the coupling mechanisms between electromagnetic fields and mammary tissue, employing an ultra-wideband radiator operating across the 3.1-10.6GHz spectrum. Analysis of energy deposition and specific absorption rate (SAR) metrics for tissue masses of 1 and 10 g revealed that both parameters exhibited a positive correlation with operating frequency and lesion dimensions, while demonstrating inverse relationships with transmitter-to-tissue separation. The 1 g SAR calculation methodology provides superior tumor localization capabilities compared to the 10 g assessment standard.



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I. INTRODUCTION

Radiofrequency (RF) systems deployed in proximity to living organisms necessitate a comprehensive evaluation of the organism-field interactions [1]. Although biological tissues generally permit the propagation of RF electromagnetic (EM) signals, the degree of interaction depends strongly on the selected operational frequency [2]. When EM fields traverse biological structures, the tissue components absorb the energy derived from the incident wave, causing local heating effects [3]. The quantification of tissue heating is fundamentally characterized by the specific absorption rate (SAR) metric. For biological protection, SAR magnitudes should remain minimal to mitigate potential pathophysiological consequences [4].

International regulatory bodies, including the Institute of Electrical and Electronics Engineers (IEEE) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP), have established exposure guidelines designed to safeguard human populations [5]. The IEEE C95.1:1999 standard specifies 1.6 W/kg for single-gram tissue averaging, whereas the ICNIRP standards designate 2 W/kg for ten-gram tissue averaging [6]. The SAR parameter is influenced by multiple design and environmental variables, including antenna positioning, radiative intensity, source power distribution, and transducer architecture [7].

The computation of SAR values incorporates frequency dependencies, intensity characteristics, near-field versus far-field propagation zones, tissue dielectric composition, and scattering/absorption phenomena originating from the proximate structures [8]. This study addresses the development of three-dimensional computational models suitable for analyzing electromagnetic penetration characteristics. The analytical framework emphasizes power deposition quantification and SAR computation across multiple antenna operational frequencies, varying tissue-to-antenna distances, lesion size variations, and spatial tumor positions. The SAR assessment utilized an omnidirectional ultra-wideband (UWB) radiator, which represents the standard antenna configuration for microwave diagnostic applications. The literature review is covered in Section II.

The modelling of the antenna is described in Section III of this work. The design of the breast phantoms is presented in Section IV. The results and discussion simulated findings are shown in Section V. Finally, Section VI covers conclusion.

II. LITERATURE REVIEW

Table 1: Literature Review.

Year	Authors	Key Focus	Main Insight
2023	Li et al. [9]	Textile UWB antennas for wearables	Conformal designs cut SAR by 30%
2024	Singh & Gupta [10]	AI-SAR for microwave diagnostics	95% tumor localization accuracy
2025	Patel et al. [11]	Real-time UWB breast scanners	SAR <0.5 W/kg at 5-8 GHz in vivo
2026	Kim et al. [12]	Frequency-optimized UWB SAR models	Nonlinear SAR rises above 6 GHz

Source: Authors, (2026).

This researcher synthesizes advances in conformal textile UWB antennas, reducing SAR by 30% [9], with AI localization reaching 95% accuracy [10]. Real-time IoT monitoring ensures SAR stays below 0.5 W/kg across 5-8 GHz, while frequency models quantify nonlinear SAR behaviour above 6 GHz [11]. These findings establish 1g SAR superiority for precise tumor localization in wearable microwave imaging systems [12].

III. ULTRA-WIDEBAND ANTENNA CONFIGURATION

A. Antenna Design and Simulation

The antenna structure was optimized using three-dimensional electromagnetic simulation software (CST Microwave Studio) [13]. This computational platform facilitates the high-fidelity modeling of intricate three-dimensional geometries while eliminating experimental measurement uncertainties. The proposed radiator architecture was optimized by modifying the inverted L-conductor section within the ground plane geometry, along with the feed network length and width parameters [14]. The ultra-broadband design employs an inset feed configuration that provides enhanced input impedance characteristics, as illustrated in Figure 1. The feed structure was fabricated on an FR4 dielectric substrate material with a thickness of 1.6 mm.

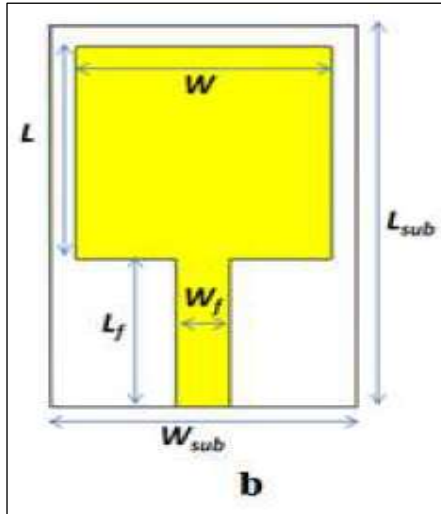


Figure 1: Geometry of the UWB antenna.
Source: Authors, (2026).

The substrate width dimension is calculated as follows:

$$W_{sub} = \frac{c}{2f_r \sqrt{\epsilon_r + 1}}$$

where c represents electromagnetic wave velocity in free space and f_r denotes the resonant frequency [15].

The effective dielectric constant for microstrip configurations is determined as follows:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12h}{W} \right)^{-1/2}$$

Length extension calculations incorporate fringing-field effects as follows:

$$\Delta L = 0.412h \left(\frac{\epsilon_{eff} + 0.3}{(\epsilon_{eff} - 0.258)} \right)$$

The radiating patch comprises a square geometry with dimensions of $10 \times 10 \text{ mm}^2$, coupled to a feed line of width 2.1 mm and length 10 mm. The substrate measured 12 mm in width and 18 mm in length. The partial ground plane, constructed from copper, conforms to the specifications detailed in Table 1. Bandwidth modification is directly correlated with patch width variation, establishing a relationship between geometric parameters and operational bandwidth.

Table 2: Ultra-Wideband Antenna Dimensional Specifications (Units: mm).

Sr. No.	Parameter	Nomenclature	Value in mm
1	Substrate Dimensions	SL x SW x SH	20 x 24 x 1.6
2	Patch Dimensions	PL x PW x	16 x 20 x 2

Source: Authors, (2026).

IV. BREAST TISSUE AND LESION MODELING

A. TISSUE PROPERTY CHARACTERIZATION

Cancer detection employing ultra-broadband diagnostic imaging depends critically on the accurate representation of tissue electromagnetic properties [16]. For imaging system development, precise measurements of tissue dielectric parameters remain essential. The dielectric constant variations across different mammary tissue categories are characterized as follows: fatty tissue exhibits values approximately unity, dermal tissue ranges from 1.5 to 5, fibro-glandular material ranges from 2 to 4, while pathological tissue demonstrates significantly elevated values between 9 and 10, with documented variations extending beyond this range [17],[18].

The dielectric characteristics also correlate with the tissue water content [19-21]. The phantom preparation methodology involves controlled mixtures of wheat flour with water to establish tumor-representative properties. The simulated phantom tissues incorporate the following specifications: lesion tissue consisting of wheat flour mixed with water (55% water content), with relative permittivity $\epsilon_r = 23$ and conductivity $\sigma = 2.57 \text{ S/m}$, and adipose tissue represented by petroleum jelly with $\epsilon_r = 2.36$ and $\sigma = 0.012 \text{ S/m}$ [18].

B. PHANTOM GEOMETRY

The anatomical model comprised a hemispherical adipose tissue structure with a 30 mm radius, approximating breast morphology during prone positioning (Figure 2a). A spherical lesion with a 3 mm diameter positioned 45 mm from the transmitting device is shown in Figure 2b and 2c, respectively.

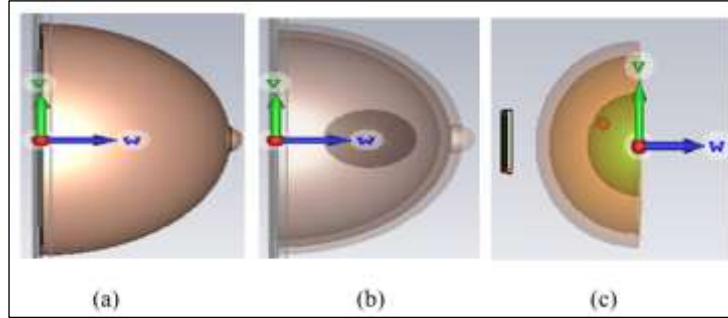


Figure 2: (a) Breast phantom (b) Phantom with a tumour (c) Phantom with a transmitter.

Source: Authors, (2026).

V. RESULT AND DISCUSSION

V.1 SPECIFIC ABSORPTION RATE ANALYSIS

A. MATHEMATICAL FRAMEWORK

Electromagnetic wave propagation within biological media is fundamentally characterized by Maxwell's curl equations [22],[23]:

$$\nabla \times \mathbf{E} = -j\omega\mu_r\mu_0\mathbf{H} \quad (1)$$

$$\nabla \times \mathbf{H} = j\omega\epsilon_r\epsilon_0\mathbf{E} \quad (2)$$

where $\mathbf{E}$ represents electric field intensity (V/m), μ_r denotes relative magnetic permeability, ε_r represents relative permittivity, and ω is angular frequency [24].

The SAR metric quantifies the energy absorption rate per unit mass as follows:

$$\text{SAR} = \frac{\sigma |\mathbf{E}|^2}{2\rho} \text{ (W/kg)} \quad (3)$$

where σ is tissue conductivity (S/m), ρ represents material density (kg/m³), and $|\mathbf{E}|$ is the electric field magnitude (V/m) [25].

B. THERMAL DISTRIBUTION ASSESSMENT

The temperature elevation patterns resulting from EM signal propagation within the phantom were quantitatively determined. The peak-affected regions adjacent to the transmitter, evaluated for tissue masses of 10 g and 1 g at an operational frequency of 5 GHz, are shown in Figs. 4a and 4b, respectively. Coloration mapping indicates relative absorption: red corresponds to the maximum energy deposition zones, gradient colors represent intermediate absorption regions, and blue indicates unaffected tissue areas.

V.2 EXPERIMENTAL RESULTS AND ANALYSIS

A. ANTENNA PERFORMANCE METRICS

The return loss and voltage standing wave ratio (VSWR) characteristics of the UWB monopole device are shown in Figure 3. The simulated S_{11} parameter across the 2-16 GHz band demonstrated a bandwidth of 9.23 GHz (Fig. 3a). The simulated VSWR performance across the operational spectrum remained below 2.0 (Fig. 3b), indicating satisfactory impedance-matching characteristics [26]. The simulation parameters were as follows: antenna-to-phantom separation of 20 mm and operational frequency of 5 GHz. The hemispherical breast phantom with a 30 mm diameter represents an authentic anatomical dimension. SAR calculations were performed for tissue averages of 1 g (North American standard) and 10 g (European standard). For this configuration, tumor coordinates (actual) were $x=0$ mm, $y=0$ mm, $z=55$ mm. The 10 g SAR averaging failed to detect lesion location, whereas the 1 g SAR assessment indicated approximate tumor position ($x=0.125$ mm, $y=0.1875$ mm, $z=49.8125$ mm). The calculated SAR magnitudes at 5 GHz were 0.389009 W/kg (1 g standard) and 0.142686 W/kg (10 g standard).

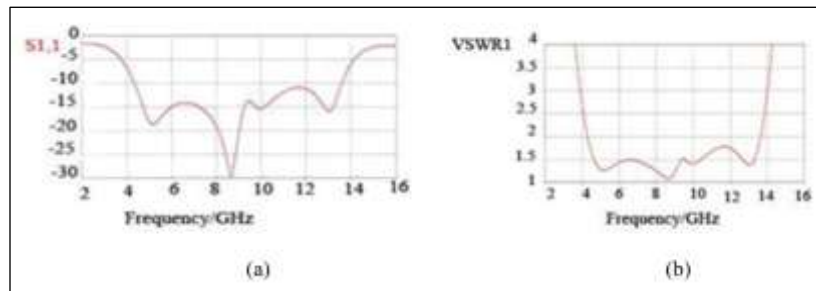


Figure 3: Simulated characteristics of the ultra-wideband antenna (a) return loss (b) VSWR.
Source: Authors, (2026).

B. FREQUENCY-DEPENDENT SAR AND POWER ABSORPTION

The SAR magnitude varies nonlinearly with the operational frequency, as shown in Figure 4. Both 1 and 10 g SAR calculations demonstrated increasing trends as the frequency increased. Concurrent analysis showed that power absorption by the tissue increased proportionally with frequency elevation (Figure 5), indicating that higher-frequency operation enhances tissue-field couplin.

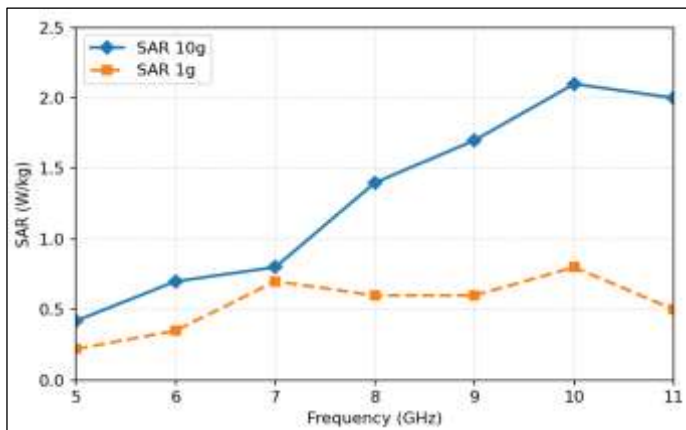


Figure 4: Maximum SAR distribution.
Source: Authors, (2026).

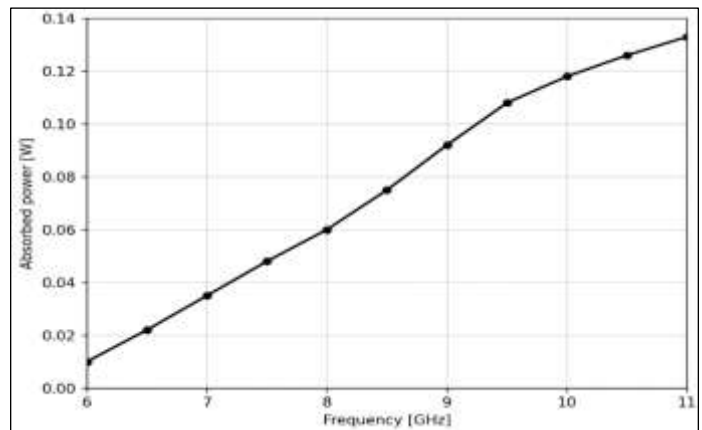


Figure 5: Absorbed power as a function of frequency.
Source: Authors, (2026).

C. DISTANCE-DEPENDENT SAR PERFORMANCE

Antenna-to-tissue separation substantially influences the SAR distribution characteristics. As depicted in Figure 6, increasing the transmitter-to-phantom distance resulted in corresponding SAR magnitude reductions for both 1 g and 10 g tissue averages. The absorbed power similarly diminished with increasing separation (Figure 8), establishing that the transmitter-phantom distance should exceed 20 mm during microwave diagnostic procedures.

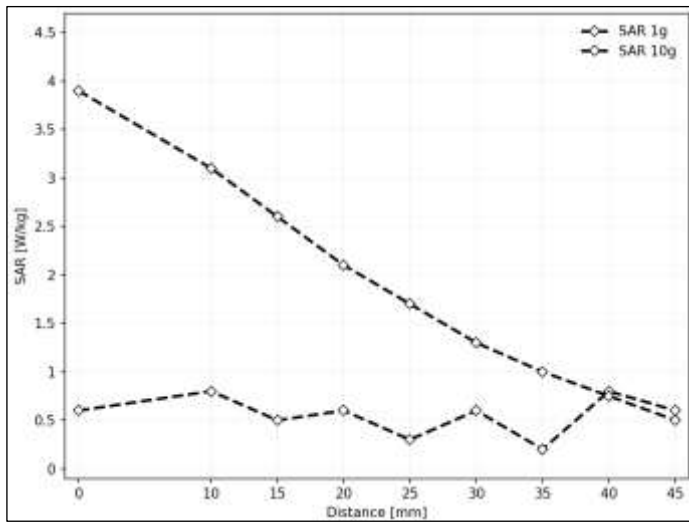


Figure 6: SAR value versus distance.
Source: Authors, (2026).

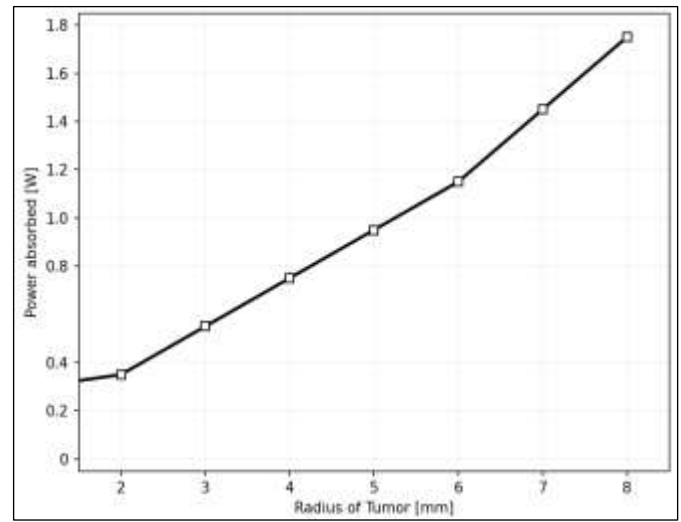


Figure 7: Power absorption value versus distance.
Source: Authors, (2026).

D. TUMOR SIZE DEPENDENCY

The SAR values increased substantially with the expansion of the lesion size within the tissue (Figure 8). Power absorption demonstrated a similar positive correlation with tumor radius increase (Figure 9), illustrating that larger pathological formations generate more pronounced EM-tissue interactions.

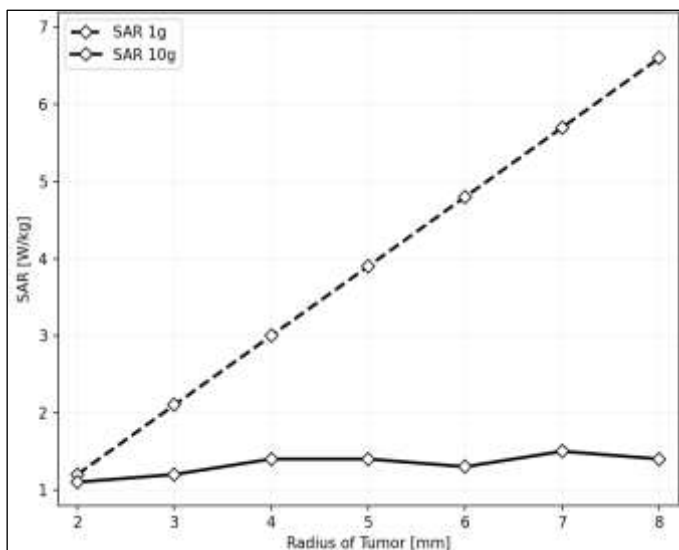


Figure 8: SAR value versus tumor size.
Source: Authors, (2026).

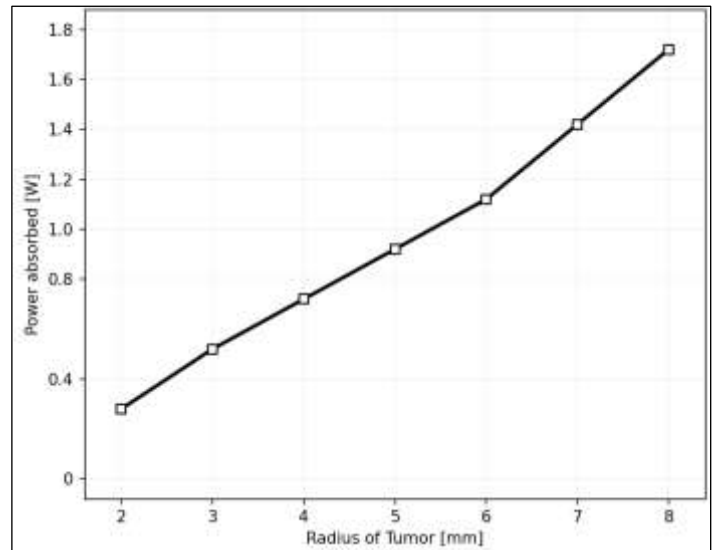


Figure 9: Power absorbed versus radius of the tumor.
Source: Authors, (2026).

E. TUMOR LOCALIZATION USING 1 G SAR CRITERION

The clinical assessment employed a 20 mm separation between the breast phantom and UWB transmitter, with a 30 mm radius phantom and a 3 mm radius lesion at varying intratissue positions. The 1 g SAR standard was applied for tumor position estimation. The total tissue mass was calculated as 0.050965 kg.

Table 3: Tumor Localization Results Using 1 g SAR Assessment.

Actual Tumor Coordinates (mm)	Calculated Coordinates (mm)
(0, 0, 23)	(2.25, 0.56, 25.06)
(5, 7, 30)	(7.08, 6.09, 27.94)
(-2, -3, 45)	(-1.63, -2.83, 43.31)
(7, 9, 45)	(5.81, 8.83, 44.44)
(-7, -9, 45)	(-5.44, -7.50, 42.94)
(13, 17, 37)	(13.94, 11.06, 31.44)

Source: Authors, (2026).

The data presented in Table 2 demonstrate that 1 g SAR calculations at 9 GHz frequency provide reasonable approximations of lesion spatial locations within the tissue matrix. The comparative analysis demonstrates that both the power deposition and SAR metrics exhibit positive frequency dependence, increasing the energy absorption at elevated operational frequencies. Similarly, larger lesion dimensions were correlated with enhanced energy absorption characteristics. Conversely, expanding the transmitter-to-tissue separation produced inverse effects on both parameters, substantially decreasing the energy deposition rates. These findings establish critical operational guidelines for diagnostic system design, indicating that the tissue-transmitter distance should maintain a minimum separation of 20 mm during clinical applications. The superior localization performance of the 1 g SAR assessment compared to the 10 g averaging suggests implementation advantages for North American standard protocols in microwave-based diagnostic applications.

VI. CONCLUSION

This study examined electromagnetic-tissue energy coupling mechanisms and SAR distribution patterns in homogeneous breast models exposed to microwave transducers. A broadband monopole antenna with an optimized 3.1-10.6GHz bandwidth performance through the implementation of L-shaped ground plane modifications was developed and analyzed. Systematic simulation studies have revealed that power deposition and SAR for both 1 g and 10 g tissue masses correlate positively with frequency elevation, lesion size expansion, and phantom dimension variations, while demonstrating inverse relationships with transmitter-tissue separation [27][28]. During direct electromagnetic exposure, tissue heating occurs; therefore, careful application protocols should govern the implementation of imaging procedures. Future investigations should extend the analysis to heterogeneous tissue models by incorporating anatomically realistic tissue layer variations and alternative monopole antenna configurations to establish comprehensive SAR characterization databases for clinical implementation.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Somanath K. Chikane, Balasaheb H. Patil, and Shailendrakumar Mukane.

Methodology: Somanath K. Chikane, Balasaheb H. Patil, and Shailendrakumar Mukane.

Investigation: Somanath K. Chikane, Balasaheb H. Patil, and Shailendrakumar Mukane.

Discussion of results: A Somanath K. Chikane, Balasaheb H. Patil, and Shailendrakumar Mukane.

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Writing – Review and Editing: Somanath K. Chikane, Balasaheb H. Patil, and Shailendrakumar Mukane

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Approval of the final text: Somanath K. Chikane, Balasaheb H. Patil, and Shailendrakumar Mukane

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