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PERSONALIZED CHRONIC WOUNDS TREATMENT BY APPLICATION OF ADDITIVE TECHNOLOGIES

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Abstract: Chronic wounds are complex, non-healing conditions that require individualized therapeutic solutions. This paper presents a digital workflow that integrates advanced wound imaging, AI-based segmentation (DeepSkin), CAD modeling, and additive manufacturing (AM) to produce patient-specific wound care devices. High-precision wound boundary detection and peri-wound segmentation enable the generation of anatomically accurate 3D models, which are converted to STL and fabricated using FDM 3D printing. Personalized dressings and covers conform precisely to wound geometry, supporting moisture control, mechanical protection, and controlled drug release. In addition, porous scaffolds can be designed to mimic extracellular matrix structures and promote tissue regeneration. This personalized approach improves healing outcomes and enables rapid, point-of-care production, reducing treatment time and costs. The proposed workflow demonstrates the potential of combining AI-driven analysis and additive manufacturing for next-generation wound care solutions and lays the foundation for integrating smart sensors and automated clinical production systems.

Keywords: chronic wounds, personalized, CAD, image analysis, additive technologies, ROI, scaffolds

1. INTRODUCTION

Chronic wounds, defined as wounds that do not progress through the standard stages of healing within a predictable time frame, are a significant and growing public health concern. These wounds often arise from underlying conditions such as diabetes mellitus, venous insufficiency, or prolonged pressure and are frequently complicated by infection, inflammation, and tissue necrosis. They affect

millions of patients worldwide and place a substantial economic burden on healthcare systems due to their prolonged treatment periods, frequent hospital visits, and the need for specialized care. Despite advances in wound management, conventional treatment methods, such as debridement, topical antimicrobials, and pressure-relieving devices, often prove inadequate, particularly when dealing with extensive wounds, infections, or those located in anatomically complex areas.

These challenges necessitate the exploration of novel, patient-specific therapeutic solutions that can adapt to the unique characteristics of each wound. Recent developments in digital health technologies offer promising pathways toward personalized medicine in wound care. Among these, additive manufacturing (AM) commonly known as 3D printing, stands out as a particularly valuable innovation. AM enables the fabrication of customized medical devices and treatment tools by layering materials based on digital models derived from imaging data. In the context of chronic wound treatment, this capability can be utilized to design and produce wound-specific bandages, drug-eluting patches, and bioengineered scaffolds that facilitate tissue regeneration. This paper investigates the application of AM in chronic wound care, focusing on the integration of advanced imaging, computer-aided design (CAD), and biocompatible material printing to produce highly tailored therapeutic treatments.

2. LITERATURE REVIEW

Chronic wounds represent a failure in the normal healing cascade, often arrested in the inflammatory phase due to ischemia, infection, or immune dysregulation. As highlighted in [1], elevated protease levels and diminished growth factor expression sustain inflammation and obstruct tissue regeneration. Clinically, these wounds manifest as painful, slow-healing ulcerations with high recurrence risk. Conventional treatment methods are often inadequate, lacking the ability to adapt to the wound's unique morphology and environment. In [2], authors emphasized that standard dressings are often ineffective and advocated for personalized approaches that consider wound depth, geometry, and biochemical profile. Accurate wound assessment is critical for individualized care. Modalities such as digital photography, thermography, and 3D surface scanning are employed to capture wound features. More recently, machine learning techniques have improved wound characterization, including margin detection and tissue classification. For example, [3]

showed that convolutional neural networks could delineate wound boundaries with over 90% accuracy, enabling the generation of high-fidelity digital wound models. These models form the basis for CAD processes, which drive the production of customized therapeutic devices through additive manufacturing (AM). AM technologies such as Fused Deposition Modelling (FDM), stereolithography (SLA), and inkjet bioprinting allow fabrication of wound dressings tailored to the patient's anatomy. In [4], researchers developed 3D-printed dressings equipped with sensors for monitoring pH, temperature, and moisture, combined with drug reservoirs for targeted release. Materials like polylactic acid (PLA) and polycaprolactone (PCL), blended with hydrogels or antimicrobial agents, enable biocompatible and functional designs. When tissue loss is significant, regenerative scaffolds fabricated via AM can support healing by mimicking the extracellular matrix (ECM). These porous structures are engineered for optimal cell adhesion, proliferation, and angiogenesis. As described in [5], stem cell-laden bioprinted scaffolds using ECM-mimicking hydrogels have shown promise in preclinical models of soft tissue regeneration. The true power of AM emerges when integrated into a digital workflow that includes wound imaging, CAD modeling, and 3D fabrication. This closed-loop process enables rapid prototyping, iterative improvements, and patient-specific interventions. Combined with telemedicine and cloud platforms, such workflows can enhance accessibility to advanced wound care technologies. Although still in early clinical adoption, the integration of imaging, CAD, and AM holds great promise for transforming chronic wound management with personalized, efficient, and biologically informed solutions.

3. METHODOLOGY

The methodology combines AI-driven wound segmentation with the DeepSkin framework and automated pixel-to-millimetre calibration for precise wound geometry extraction. Segmentation masks are converted into 3D point clouds and mesh models, which are then transformed into STL files for custom-fit dressing/cover design. These models are refined in Blender and prepared for FDM 3D printing using Cura [6], ensuring anatomically accurate, patient-specific wound dressings.

3.1 The DeepSkin Framework

Recent advances in artificial intelligence and computer vision have enabled powerful tools for medical image analysis, including wound care. A prominent example is the DeepSkin framework, a deep learning-based system designed for automatic recognition, segmentation, and classification of chronic wounds. By employing convolutional neural networks (CNNs), DeepSkin enhances wound assessment with greater consistency, speed, and objectivity compared to manual methods [6]. Architecturally, DeepSkin often uses encoder-decoder networks such as U-Net or DeepLabV3+, sometimes augmented with attention mechanisms or dense skip connections to preserve spatial detail. It is trained on annotated wound datasets collected under varying imaging conditions, promoting generalization across diverse clinical scenarios [3]. Although multi-class segmentation of tissue types, e.g., necrotic, sloughy, granulating, and epithelial, is still challenging, promising classification results have been achieved in controlled settings. To improve performance, pre-processing steps like color normalization and contrast adjustment are applied, along with data augmentation techniques such as flipping, rotation, and scaling. Post-processing methods, including morphological operations or conditional random fields (CRFs), further refine the wound masks to enhance boundary accuracy. These segmentation outputs can be converted into 3D models using techniques like

photogrammetry or structured light, allowing integration with CAD tools. This enables the design of personalized interventions, such as custom-fit dressings or scaffolds fabricated through additive manufacturing (AM). Some experimental studies have combined these constructs with controlled drug-release profiles, pointing toward individualized wound therapies [7]. In addition, DeepSkin supports longitudinal monitoring by quantifying changes in wound area and tissue composition over time, making it a potentially valuable tool for evidence-based clinical decision-making and outcome prediction [8].

3.2 Applications of Additive Manufacturing in Chronic Wound Care

Additive manufacturing (AM) provides a transformative platform for producing highly customized therapeutic solutions for chronic wound management [9-11]. By leveraging patient-specific wound geometry obtained from imaging and segmentation (e.g., via DeepSkin), AM can be used to produce advanced wound care products that conform precisely to the affected area. One major application is the development of custom-fit wound dressings or anatomical sleeves that match the topography of irregular wound surfaces. These dressings can be designed with multilayered structures, integrating materials that regulate moisture, delivering antimicrobial agents, or promote cell proliferation through bioactive coatings. Additionally, AM enables the production of bioresorbable drug-delivery systems, such as patches and microneedle arrays, that can release therapeutic agents in a controlled manner tailored to the wound's healing stage. In more advanced applications, biocompatible scaffolds fabricated using polymers such as PCL, PLA, or gelatine-based hydrogels are used to support tissue regeneration. These scaffolds are engineered to mimic the extracellular matrix (ECM) by tuning porosity, surface texture, and mechanical strength, thus promoting angiogenesis, epithelialization, and collagen deposition in the wound bed.

Moreover, AM allows for the integration of sensor elements (e.g., pH, temperature, moisture) within smart wound dressings, enabling real-time monitoring of wound status and adaptive treatment strategies. These capabilities support the vision of personalized wound care, reducing healing times, minimizing infection risk, and improving patient comfort.

3.3 Custom-Fit Wound Dressings Created Through Additive Manufacturing

Additive manufacturing (AM) has revolutionized chronic wound care by enabling the production of custom-fit dressings tailored to a patient's wound shape. Unlike conventional products, AM uses 3D wound models from imaging tools like DeepSkin to guide the precise deposition of biocompatible materials [12]. This ensures a personalized fit that promotes healing by maintaining moisture, reducing dead space, and conforming to complex anatomical areas like joints [10]. AM also supports multi-material fabrication. Inner layers may incorporate hydrogels infused with antimicrobials or growth factors, while outer layers offer protection against external contaminants [11]. By adjusting parameters such as porosity, infill, and thickness, clinicians can fine-tune mechanical properties. Features like microchannels further support oxygen exchange and fluid drainage. This entire workflow, from imaging to fabrication, can be done on-site, reducing treatment delays and supply issues. AM extends to producing rigid and semi-rigid supports that redistribute pressure in conditions like diabetic foot ulcers (DFUs). Orthoses such as 3D-printed braces or wraps, based on detailed scans, are printed in biocompatible thermoplastics like TPU or PLA, enabling customization of elasticity and support [10]. These supports protect the wound by offloading pressure without creating new points of stress. CAD tools allow integration of complex geometries, such as honeycomb structures, to reduce weight and enhance breathability, with airflow channels aiding thermal and moisture control. Such supports can also include bioactive inner components,

like hydrogel or medicated films, for simultaneous wound protection and treatment. This hybrid approach merges mechanical function with therapeutic delivery, enabling localized release of antimicrobial or regenerative agents. A major benefit of AM is its adaptability: as the wound heals, updated models can be reprinted with minimal waste and rapid turnaround. This decentralized, point-of-care production is feasible even in hospitals or clinics using desktop 3D printers, improving access in remote or underserved settings. Clinical evidence highlights improved healing outcomes, patient comfort, and adherence when using personalized AM solutions [10]. As adoption grows, AM holds strong promise for scalable, effective, and patient-specific wound care.

3.4 The workflow for the creation of custom fittings by using FDM printing

The workflow during the preprocessing phase automatically performs a pixel-to-millimetre calibration routine for wound-assessment images that include a plastic ruler (Figure 1). The images are captured with mobile phone cameras using a designated ruler to determine pixel spacing. The general procedure for processing images is described in detail in [12]. The initial images are pre-processed in GIMP, a free software, by rotating the ruler horizontally and cropping the image. The algorithm is:

1. Pre-processes the cropped ruler strip,
2. Extracts the tick marks by adaptive thresholding,
3. Projects the binary image onto the X-axis to obtain a 1-D signal,
4. Detects peaks in that signal to localize tick,
5. Computes the median inter-peak distance to yield pixels per millimetres, and
6. Optionally overlays the detected ticks for visual verification.

To create a custom fit for various ulcers, a workflow for designing the 3D model of the nylon dressing cover was developed. The workflow diagram is shown in the following Figure 2. This diagram presents a step-by-step

workflow for generating custom-fit wound covers. It integrates the DeepSkin deep learning framework and Fused Deposition Modeling (FDM)-based additive manufacturing. The

process begins with an image database that serves as a source of chronic wounds images.



Figure 1. The definition of the millimeters lines

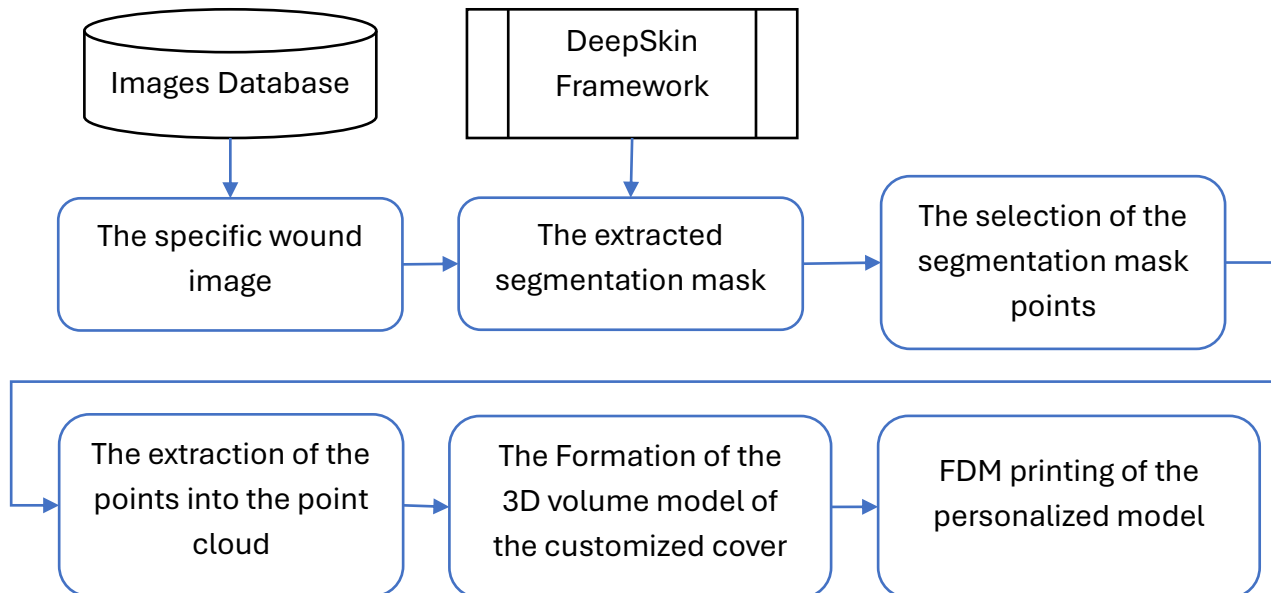


Figure 2. Workflow for Personalized Wound Dressing Cover Design Using DeepSkin and Additive Manufacturing

A specific wound image is selected and processed through the DeepSkin framework, which performs segmentation to isolate the wound region and generate a segmentation mask (Figure 3). The DeepSkin framework application is defined through several steps:

A. Wound and Peri-Wound Surface Extraction Pipeline - We developed a Python-based pipeline using the DeepSkin framework for automated segmentation and 3D modeling of chronic wounds. The process consists of the following key stages:

B. Image Acquisition and Preprocessing - The input image of the wound is read using OpenCV and converted from BGR to RGB color space to maintain compatibility with visualization and analysis libraries.

C. Segmentation Using DeepSkin - DeepSkin's wound segmentation function is applied to the RGB image, generating a three-channel binary mask that identifies the wound, peri-wound area, and background.

D. Mask Extraction and Visualization

From the segmentation output, individual binary masks for the wound and body surface are extracted. The peri-wound region is then calculated using morphological expansion, and post-processed with an infill operation to ensure completeness. Visualization of each mask overlay on the original image is performed for verification.

E. Wound and Peri-Wound Area Estimation - Using `cv2.findContours()` and pixel spacing (set to 1/8 mm), the planar area of the wound and peri-wound masks is calculated and converted to real-world square millimetre units.

F. 3D Mesh Generation - The peri-wound mask is converted into a 3D model by turning it into a solid volume. We use the marching cubes method from skimage measure to generate a surface mesh from the volumetric representation of the binary mask. The mesh is scaled based on the real-world pixel spacing

and then exported to STL format using the trimesh lib.

G. Preservation of Real Dimensions -

Unlike previous simplified methods, this pipeline ensures that the spatial dimensions of

the extracted mesh are consistent with the real wound size by strictly applying calibrated pixel spacing and accounting for extrusion depth.

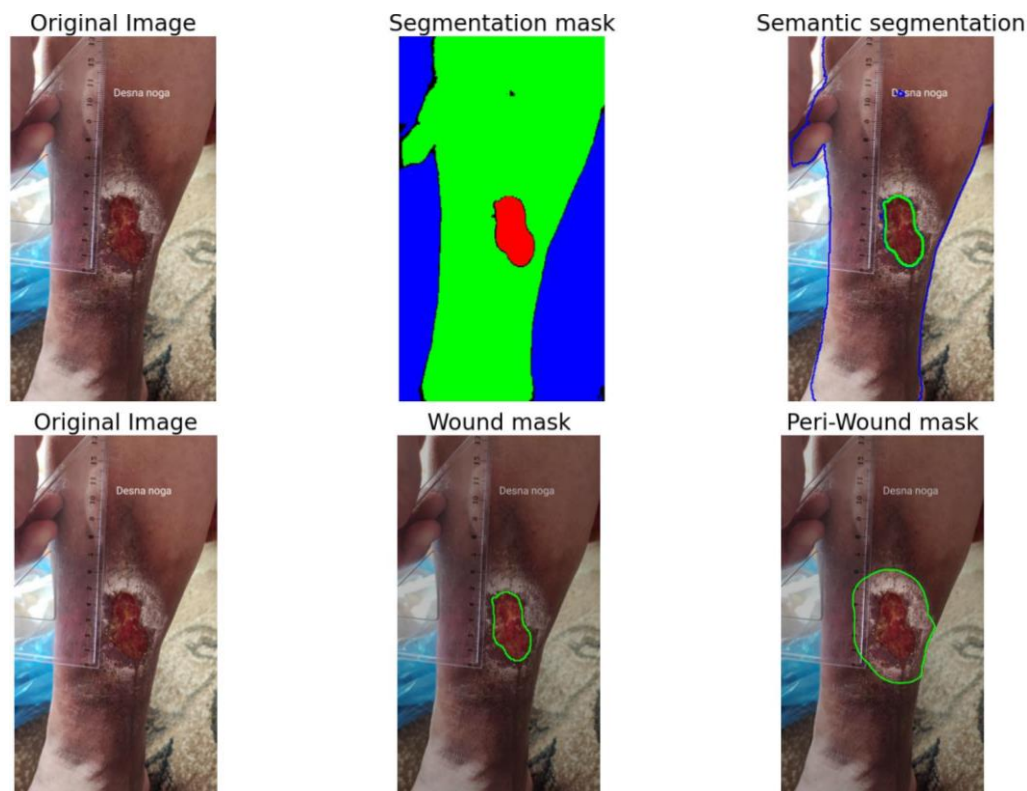


Figure 3. The process of segmentation masks and boundaries creation

In this case, we use a peripheral mask as a basis for the dressing development, to cover a wider wound area. After segmentation, the system allows for selecting relevant mask points that define the boundary, area, and shape of the wound. These points are then extracted and converted into a point cloud and respective mesh, which serves as the foundation for creating a 3D digital model. The point cloud provides an accurate spatial representation of the wound surface, used to generate a 3D volume model that matches the patient's wound and surrounding tissue. This 3D model is designed to conform to the anatomical contours, ensuring an optimal therapeutic fit. The final step in the process is FDM printing of the personalized model using elastomer material (nylon).

The calculated areas are: Wound boundary area: 36532.00 pixels (745.55 mm²); Peri Wound boundary area: 140643.50 pixels

(2870.28 mm²). The 3D model designed for FDM was created by converting segmented peri-wound masks into printable geometries. Starting with clinical images, the wound and surrounding tissue were identified using a DeepSkin framework. The output mask was then processed to define both the wound boundaries and the extended peri-wound region. From this binary image, a contour-based approach was used to calculate the surface area and extract spatial information relevant for 3D modeling (Figure 4). The pixel-based area estimates were converted into real-world dimensions using calibrated pixel spacing. Based on the extracted wound geometry, a three-dimensional mesh was generated to represent the shape of the wound site (Figure 4). The mesh was formed by extruding the wound boundary to a set thickness, creating a volumetric shell that could serve as a custom-fit wound dressing. To better conform to

anatomical contours, an elevation profile was applied so that the central area of the wound cover gradually rose relative to the periphery. This design mimics the curvature of biological tissues, supporting therapeutic functions such as pressure distribution and fluid management. The digital mesh was exported in STL format and imported into a 3D modeling environment (Blender Software) for inspection and refinement [13]. In this environment, the model could be smoothed, adjusted, or structurally improved to ensure stability during printing and comfort during clinical use (Figure 4). Once

finalized, the model was sliced using computer-aided manufacturing software (Cura, Figure 5), where printing parameters such as layer height, infill, and material type were configured. The resulting G-code was then used to produce the custom wound dressing cover using a medical-grade elastomeric material, Figure 6.

This workflow demonstrates a streamlined process for creating personalized, anatomically accurate wound care solutions, ready for production using low-cost and widely available FDM 3D printing technologies.

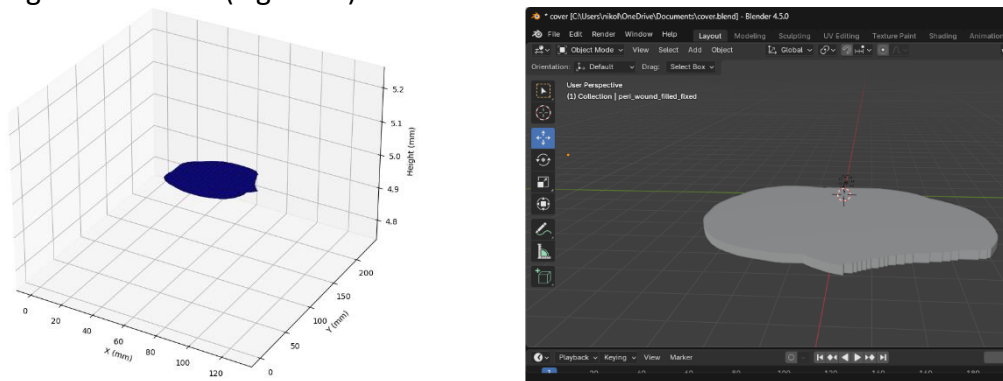


Figure 4. The mesh model of the per-wound segmentation mask (left) and The STL model processed in Blender Software (right)

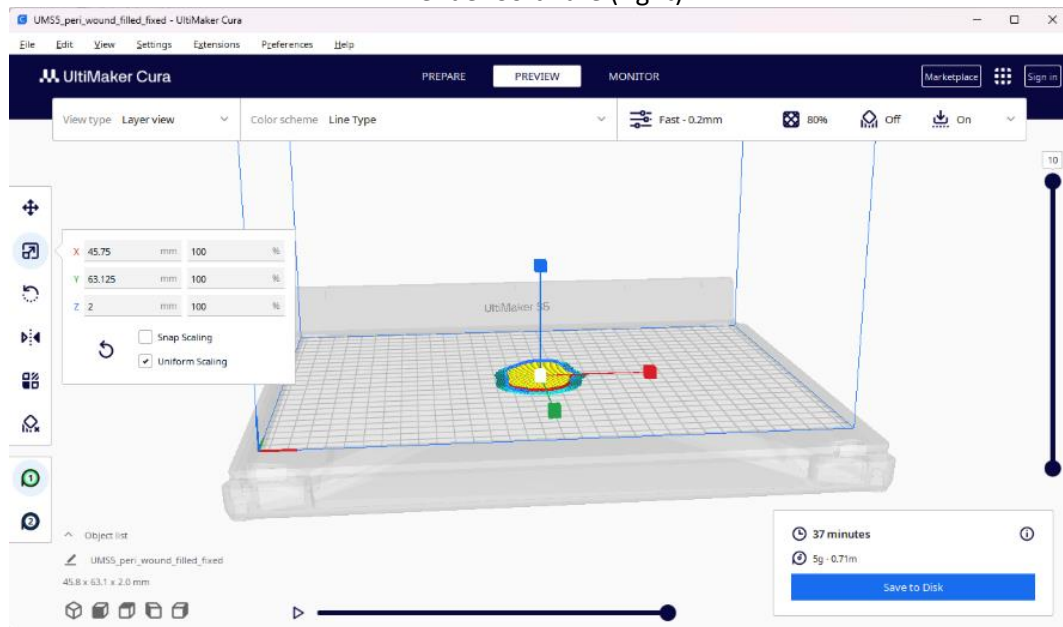


Figure 5. The model processed in Cura Software



Figure 6. The FDM printing process and Physical nylon model of personalized wound dressing cover

4. CONCLUSION

This study outlines a workflow for personalized treatment of chronic wounds using additive manufacturing technologies. By combining advanced imaging, AI-based segmentation (DeepSkin), CAD modeling, FDM 3D printing, and other additive technologies [14], it is possible to create custom-fit wound dressing and structural supports tailored to individual patient anatomy. The methodology ensures geometric accuracy, promotes healing through biomaterial design, and allows for real-time monitoring when paired with smart sensors. The approach shows potential to improve clinical outcomes, shorten healing times, and enhance patient comfort. Future work will focus on clinical validation and expanding capabilities toward automated, on-site wound care production systems.

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