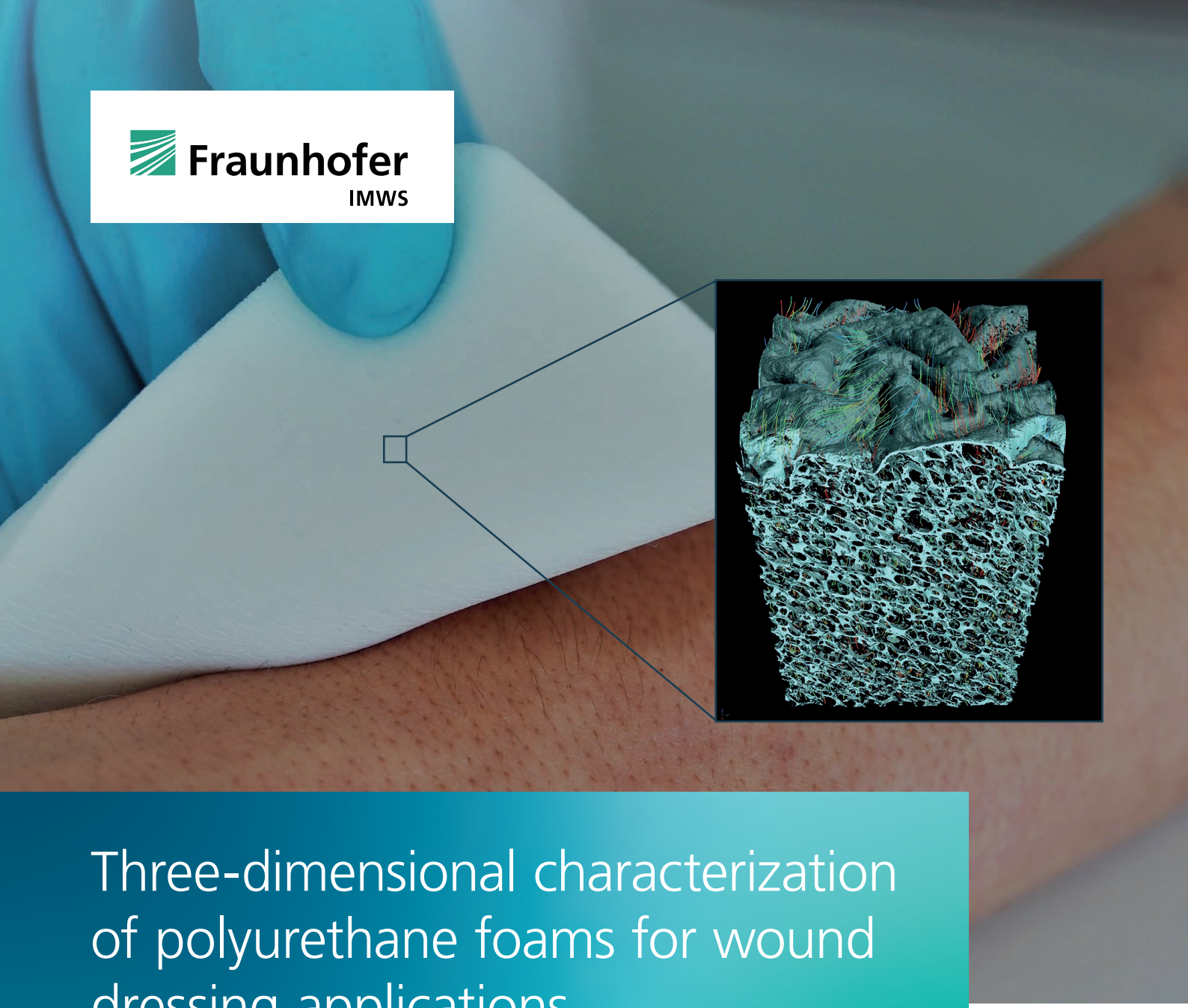
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Three-dimensional characterization of polyurethane foams for wound dressing applications

Matthias Menzel, Juliana Martins de Souza e Silva, Andrea Friedmann, Christian E. H. Schmelzer

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Introduction

Wound healing is a complex and dynamic process involving the interaction of different cell types, matrix components and biological factors in an aqueous environment. Wound exudate production is intrinsic to a normal wound healing process and generally reduces over time.

However, wound healing may be compromised if there is inflammation or an excessive production of exudate. It is also impaired if the composition of the exudate has an imbalance of enzymes and their inhibitors, or contains large amounts of toxins. Therefore, the management of exudate to achieve a balanced environment is essential for improved wound healing.

Foam dressings are particularly effective in the treatment of chronic wounds, where excessive exudate formation is problematic. They are among the best dressings available for healing chronic wounds. Foam dressings are commonly made of polyurethane (PU) and have a smooth contact surface with the wound. They provide thermal insulation while are permeable to gases, provide cushioning protection to the wound, and leave no fibers or residues on it.

Today, there are numerous foam dressings that address exudate absorption in various ways. Many foams absorb the exudate, some have the capacity to wick horizontally, thus increasing absorption capacity of the fluid as it spreads through the whole dressing. In addition to absorption capacity, water vapor permeability is another important parameter for determining the total fluid-handling capacity of foam materials.

When developing novel, application-optimized wound dressings, the ability of a dressing to retain hydration and allow gas exchange must be considered. In this context, X-ray micro-computed tomography (micro-CT) is a characterization technique that can provide valuable information. It not only enables three-dimensional (3D) visualization of wound dressings, but also the evaluation of structural properties such as the dressing porosity. The data can also be used to simulate the ability of foams to transport gases and liquids.

The present white paper presents the detailed micro-CT characterization of polyurethane foams used as wound dressings in medical care.

3D micro-CT characterization of PU foams

In this work, we imaged three different PU foam sheets after cryo-fracture preparation, a pure foam (S1) and two wound dressings (W1 and W2).

Imaging instruments
For X-ray microcomputed tomographic imaging (micro-CT), we used a nanomex NF 180 E (GE/Phoenix, Hannover, Germany) equipped with a diamond X-ray source operating at 60 kV and 160 µA.

All samples were exposed to a total of 1000 projections (360 degrees) with an exposure time of 2.5 s per projection. The voxel size in the final volumes varied between 5 and 7 μm^3 and for each sample the volume analysed and used in the simulations was 1,765 μm^3.

We used a Quanta 3D (FEI, USA) scanning electron microscope (SEM) operating at 5 kV to image the samples fixated on top of a metallic stub and sputtered with 3 nm of palladium.

Visualization software
The software VGSTUDIO MAX V3.4 (Volume Graphics, Heidelberg, Germany) was used for volumetric visualization of the samples and the linear flow characteristics were simulated with the add-on Transport Phenomena Simulation Module.

Morphology and shapes of PU foams
Images obtained by SEM (Figure 1, 1st row) show that these foams are characterized by an open cell structure of round shaped interconnected pores with thin walls.

Similar images can be obtained with micro-CT (Figure 1, 2nd row), which show a similar foams morphology.

The three-dimensional image (Figure 1, 3rd row) shows the spatial distribution of PU foams walls in which the open cell morphology can be easily visualized.

Effective void and the tortuosity
We used the volumetric micro-CT data to estimate the effective void and the tortuosity of the porous path. Effective void is a representation of the porosity of the sample. It was calculated as the ratio of pore-related voxels over the total number of voxels (pores and walls) in the selected volume of analysis.

The PU foams imaged have high porosities of 86.5% for S1, 89.8% for W1 and 91.6% for W2.

Tortuosity is another important property in the study of transport and gas/fluid flux phenomena in porous materials. Though it may have different definitions and estimation approaches, the tortuosity gives a measure of the deviation of a given species from a straight path moving through a sample and is, thus, absolutely relevant to applications where a fluid moves through porous materials such as PU foams.

The tortuosity is given here by the ratio of the length of tortuous path within the cells (and holes interconnecting them) and the length of the Euclidean distance between the beginning and end of the path. Therefore, a straight path would have a tortuosity of 1.0. The values found were equal to 1.1 for all PU foam samples.

Wall thickness of PU foams
The high quality of the volumetric images enables the analysis of the PU foams wall thickness (Figure 1, 4th row). The mean cell wall thickness estimated from the three-dimensional data is 39.5 ± 0.18 µm for S1, with a maximum wall thickness of ca. 130 µm, and the mean cell wall thickness for W1 is 19.2 ± 0.16 µm, with a maximum value of 40 µm. For the sample W2, the thicker wall has less than 80 µm and the mean wall thickness is 23.6 ± 0.37 µm.

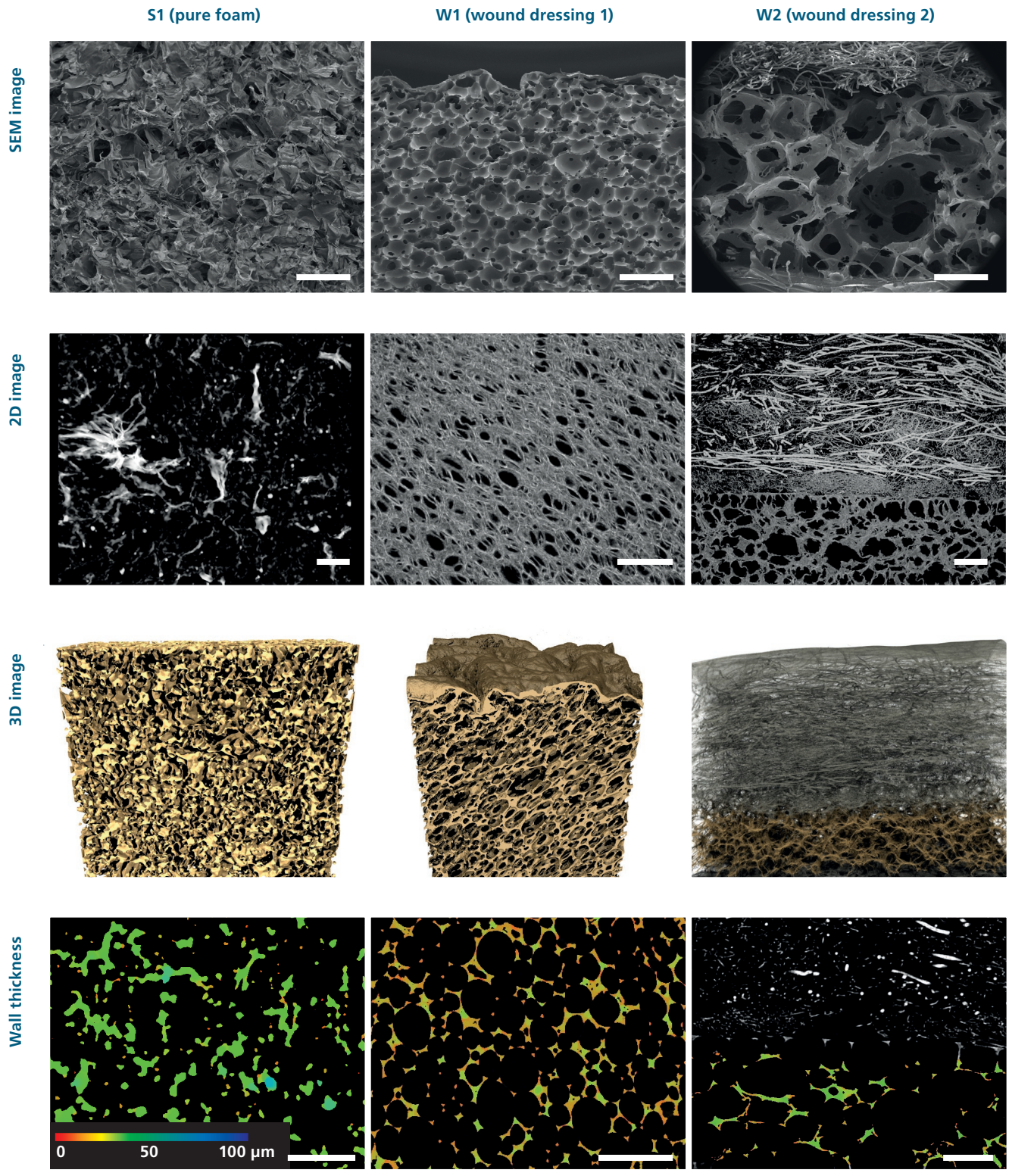


Figure 1. Images of samples S1, W1 and W2 obtained by SEM (1st row) and corresponding 2D X-ray image (2nd row) and 3D X-ray image (3rd row) obtained with micro-CT. Scale bar: 500 µm. Images from wall thickness analysis show a thick slab slice (500 µm) with a colour-thickness map of the walls (colour scale for all samples on the left). Scale bar: 500 µm.

Foam cell estimation

Using the micro-CT volumetric data, we also analysed the PU foams cells (Figure 2 and Table 1).

While sample S1 has a larger population of smaller cells (green, blue and yellow cells), sample W1 is characterized by larger round-shaped cells (cells pseudo-coloured in pink) and sample W2 is the PU foam with the largest cells. Sample S1 is the only one that has both interconnected and isolated cells. The inter-connectivity of the cells is the highest in sample S1, and the lowest in sample W2, and the volume of cells interconnected is the lowest for sample S1 and the highest for sample W2.

Table 1. Cells analysis of samples S1, W1 and W2 estimated using the micro-CT volumetric data.

Sample	Number of cells connected	Volume of cells connected [µm³]	Volume of isolated cells [µm³]
S1	18,319	2.481×10^6	15,694
W1	5,710	7.009×10^6	0
W2	1,816	1.292×10^7	0

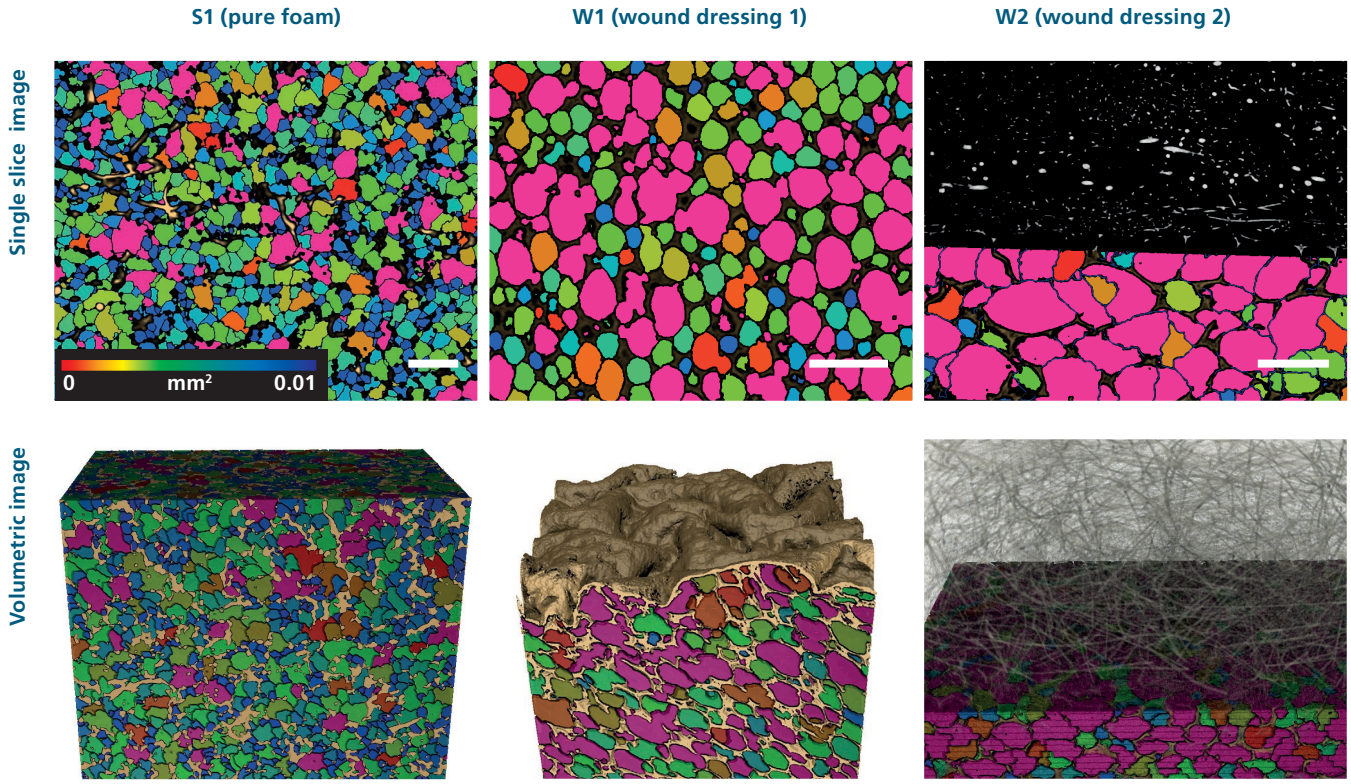


Figure 2. Analysis of the volume of cells of samples S1, W1 and W2 using the micro-CT volumetric data. Top: single slice (scale bar 500 µm), and bottom: volumetric representation, with the foams structure in yellow tones and individual cells with different colours according to their volumes.

Transport simulation based on micro-CT data

The volumetric micro-CT data of real PU foams can be used to simulate the linear permeability. In an exemplary simulation of the transport of water within these foams, we used as transport simulation parameters water at 37 °C (dynamic viscosity 6.91518 $\times 10^{-4}$ Pa·s), at a pressure difference of 1 Pa between two opposite surfaces of the foams and considering the side surfaces of the micro-CT volume closed.

The simulated flow lines can be visualized and illustrate the direction and the flow rate (Figure 3, 2D images on top and volumetric images on the bottom). The total flow rate is different among the samples (Table 2), increasing with the order W1<S1<W2. The most permeable sample is W2, which is the one with the largest interconnected cells, and it is the one showing the largest pressure gradient.

Table 2. Permeability simulation performed on real PU samples micro-CT volumetric data.

Sample	Total flow rate [m³/s]	Absolute permeability [mD]	Pressure gradient [Pa/m]
S1	2.0×10^{-9}	542,019	225
W1	2.5×10^{-10}	96,985	230
W2	4.6×10^{-7}	1,235,070	1,087

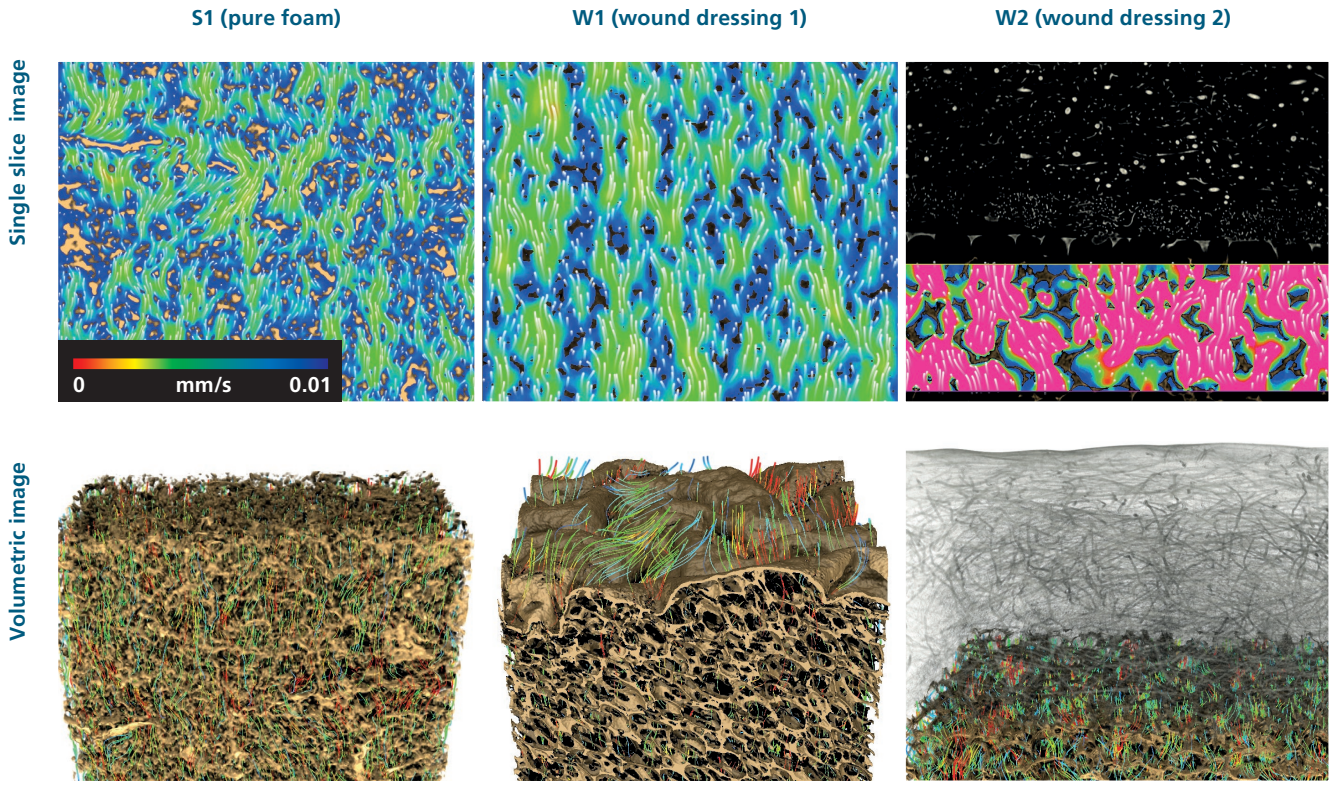


Figure 3. Flow lines of samples S1, W1 and W2 simulated using the micro-CT volumetric data. Top: single slice, and bottom: volumetric representation.

Conclusion

The morphological and transport properties of wound dressing foams are relevant parameters for the design of dressings used for the regeneration of challenging, non-healing wounds. This type of detailed morphological quantitative characterization is possible through micro-CT. It enables non-destructive three-dimensional imaging of foam samples as large as some centimeters with resolution of some tens of micrometer without the need of a special sample preparation protocol. Here, micro-CT was successfully applied to visualize and quantitatively characterize the morphology of the walls and empty spaces in PU foams.

Moreover, the volumetric data of the real PU foams were used for the simulation of the transport behavior of the foams, which is a relevant information when considering the dressing ability to absorb fluid and donate water to a dry wound.

These analyses are not limited to PU foams, and similar imaging and detailed quantitative characterization can be done with other types of materials.

In our labs, for example, we have already performed similar analysis of protein-based sponges as well as fibrous materials.

Imprint

Authors
Matthias Menzel
Dr. Juliana Martins de Souza e Silva
Dr. Andrea Friedmann
PD Dr. Christian E. H. Schmelzer

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Dr. Christiane Lindner

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Contact

PD Dr. Christian Schmelzer
Head of the Department
Biological and Macromolecular Materials
Tel. +49 345 5589 116
christian.schmelzer@imws.fraunhofer.de

Fraunhofer Institute for Microstructure of Materials and Systems IMWS
Walter-Huelse-Str. 1 | 06120 Halle (Saale) | Germany
www.imws.fraunhofer.de

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