Revealing Microstructural Dynamics in Pharmaceutical Materials with Advanced X-ray Imaging and Analysis

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X-rays have long served as a powerful probe of structure. Today, they are becoming an equally powerful probe of function. In pharmaceutical science, this transition is especially significant. The central challenges of modern formulation design, e.g., polymorphism, amorphous stabilization, liquid uptake, compaction, and performance prediction, cannot be fully understood from static measurements alone. They require methods capable of following structural change as it happens.

This talk will show how advanced X-ray imaging and analysis can reveal the dynamic microstructural behavior of pharmaceutical materials. Using synchrotron-based microtomography, in situ experiments, neural-network-assisted image analysis, and diffraction-based methods such as Rietveld refinement, we can directly observe how heterogeneous formulations interact with liquids, reorganize under compression, and evolve across multiple length scales. These processes are not merely microscopic details; they are the structural basis of pharmaceutical function [1].

Drawing on experiments performed at the TOMCAT beamline of the Swiss Light Source, I will discuss how dynamic X-ray methods provide new insight into liquid imbibition in particulate media, compaction-induced structural transformation, and the relationship between crystallinity, microstructure, and drug delivery performance [1]. The results illustrate how advanced characterization can guide the design of biocompatible and functional pharmaceutical systems, including formulations aimed at extending established delivery routes such as buccal administration through orally dispersible microcapsules [2,3].

Beyond specific case studies, the talk advances a broader perspective: pharmaceutical materials should be understood not only as compositions and phases, but as evolving microstructured systems whose performance emerges over time. Advanced X-ray imaging and analysis make this perspective experimentally accessible, offering not only improved characterization but also a route toward a more predictive, mechanistic, and function-oriented science of pharmaceutical formulation.

[1] S. Waldner et al, Heliyon (2024), Feb 12;10(4):e26025
[2] J. Kost et al, Adv. Funct. Mater. (2023), 33: 2303333.
[3] J. Kost et al, Eur J Pharm Biopharm. (2025), Sep:214:114785

The presented results include work by Dr. Samuel Waldner conducted within the scope of his PhD project, as well as work by Dr. Jonas Kost on microcapsules. Special thanks go to Dr. Christian M. Schlepütz for acquiring and analyzing the images at the TOMCAT beamline.