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Diffusion–Agglomeration Behavior of Magnetic Nanoparticles in Magnetic Hyperthermia

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Magnetic hyperthermia therapy (MHT) utilizes magnetic nanoparticles (MNPs) that generate heat under an alternating magnetic field (AMF) for localized cancer treatment. Precise control of the heating range is essential to avoid damage to surrounding healthy tissues, yet remains difficult to predict in practice. This is because MNPs can diffuse within tumor tissue while their agglomeration state changes during diffusion, thereby affecting the resulting heat distribution. In this study, hydrogels with tunable average mesh sizes (ξ) were employed as tumor-mimicking materials to investigate how diffusion and agglomeration of MNPs influence thermal distribution.

Acrylamide hydrogels were prepared with average mesh sizes estimated from viscoelastic measurements to range between 12 and 38 nm. MNP dispersions (average particle diameter $\approx$ 18 nm) were injected into cavities formed within the hydrogels, and diffusion behavior was examined on a temperature-controlled stage at 35 ℃. After diffusion, the hydrogels were freeze-dried and analyzed by scanning electron microscopy (SEM), revealing mesh-size-dependent agglomeration structures. Smaller mesh sizes ($\xi \approx$ 12 nm) promoted the formation of large, compact agglomerates, whereas larger mesh sizes ($\xi \approx$ 30 nm) produced smaller and more dispersed agglomerates (Fig. 1(a)).

To investigate how these agglomeration structures affect heat distribution, molecular dynamics simulations in porous media were performed. The hydrogel network was represented by randomly distributed cylindrical obstacles, while the mesh size was controlled by varying the number of cylinders. After diffusion reached equilibrium, an alternating magnetic field was applied in the simulations to evaluate the resulting thermal distribution. The results indicate that smaller mesh sizes produce localized heat concentration due to dense agglomeration, whereas larger mesh sizes yield a more uniform temperature distribution (Fig. 1(b)).

These findings suggest that diffusion and agglomeration of MNPs within tumor tissue strongly influence thermal distribution during magnetic hyperthermia. Experimental validation of the simulation results under an alternating magnetic field will be pursued in future work. This study provides new insight into the relationship between nanoparticle diffusion, agglomeration, and heat distribution, forming a basis for improved control of the heating range in magnetic hyperthermia therapy.

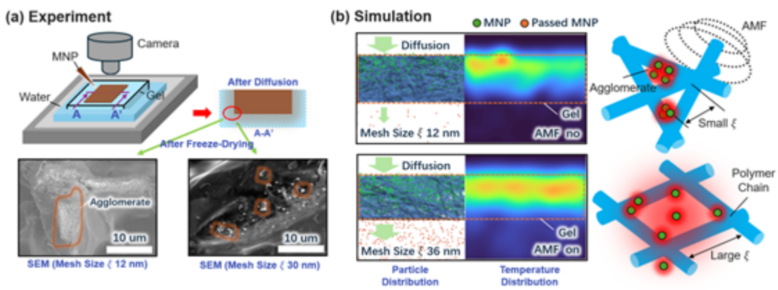

Figure 1: Fig.1(a) Diffusion and aggregation of MNPs in hydrogels with different mesh sizes, characterized by SEM after freeze-drying. (b) Simulation in porous media ($\xi \approx$ 12 and 36 nm) showing mesh-dependent aggregation and resulting differences in thermal distribution under AMF.

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