Super-resolving particle diffusion heterogeneity in porous hydrogels via high-speed 3D active-feedback single-particle tracking microscopy

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ABSTRACT: Nanoparticle diffusion in 3D porous structures is critical to understanding natural and synthetic systems but remains underexplored due to limitations in traditional microscopy methods. Here, we use 3D Single-Molecule Active-feedback Real-time Tracking (3D-SMART) microscopy to resolve nanoparticle dynamics in agarose gels with unprecedented spatiotemporal resolution. We highlight 'hopping diffusion', where particles intermittently escape confinement pockets, providing insights into hydrogel microstructure. Long, highly sampled trajectories enable extraction of kinetic parameters, confinement sizes, and thermodynamic barriers. This study demonstrates 3D-SMART's ability to probe particle-environment interactions at super-resolution (~10 nm in XY and ~30 nm in Z) in 3D, offering new perspectives on nanoparticle diffusion and the structural dynamics of porous materials, with implications for drug delivery, material science, and biological systems.

INTRODUCTION

In recent years, the development and application of single-particle tracking across many fields has been widespread.[1-4] However, nanoparticle (NP) diffusion and interaction within 3D structures remain underexplored. Nanoparticle diffusion within porous microstructures is scientifically intriguing and crucial in both natural and synthetic systems. Porous microstructures dramatically

impact the diffusion and penetration of nanoparticles. For example, mucus clearance acts as a primary barrier against viral infection and serves as an obstacle to be overcome for intranasal drug delivery.[5, 6] In gel electrophoresis and column chromatography, the diffusion of nanoparticles within complex 3D environments may provide critical structural characterization.[7]

Electron and force microscopies are common tools for studying the structure and mechanical properties of hydrogels and other microporous structures. Unfortunately, both typically involve perturbative experimental requirements that irreversibly alter the microstructures and cannot resolve particle dynamics within the hydrogel.[8, 9] Single-particle tracking (SPT) microscopy, or microrheology, is a frequent tool for studying the interaction of nanoparticles and microstructures.[10] Trajectories of single particles are usually achieved using image-based methods, in which the particle of interest is imaged sequentially, and localizations are concatenated into a trajectory.[2, 11] However, limitations exist for image-based tracking methods in terms of observation duration, lack of spatiotemporal resolution, and restriction to two-dimensional motion.[12-14] When particle motion is confined to two-dimensions (and just one focal plane), the temporal resolution is limited by the time it takes to collect one image, determine by the number of pixels and pixel dwell time for confocal methods, and camera exposure and readout for widefield methods. However, for three-dimensional processes, the particle localization rate is limited by the volumetric imaging rate, which is the single focal plane imaging rate multiplied by the number of planes required, dramatically decreasing the temporal resolution. One approach to break this volumetric imaging bottleneck is to apply point spread function (PSF) engineering to encode axial information into the 2D image of a single particle. While most PSF engineering approaches are restricted to an axial range of a few microns,[15] more recent PSF engineering techniques were able to extend the axial range to tens of microns with complex phase modulations and specially designed optics.[16, 17] However, the scattering induced by the thick and complex 3D matrix will distort PSF patterns and pose a further challenge to PSF engineering methods. An alternative approach called fcsSOFI,[7, 18] developed by Kisley *et al*, combines super-resolution optical fluctuation imaging (SOFI) and fluorescence correlation spectroscopy (FCS) and is a powerful tool to characterize spatial and diffusion information within porous materials. fcsSOFI overcomes the problem with limited sampling in SPT but sacrifices dynamic information that can be extracted from single particle trajectories. Also, in most applications of the methods mentioned above, single-particle trajectories are very challenging to understand due to high noise and short

observation time, diminishing the potential to understand the behaviors of individual particles in detail. Short, noisy, and low sampling rate trajectories limit the knowledge that can be extracted. Often, the best that can be expected is the measurement of a diffusion coefficient or extraction of non-Brownian behavior from an ensemble mean-square displacement (MSD) analysis. Long, highly sampled, three-dimensional trajectories are needed to extract the structure and dynamics of porous materials. In this work, we demonstrate that active-feedback 3D single-particle tracking microscopy is well-suited for super-resolving gel structure and dynamics in three dimensions.

Recent years have seen a wide range of applications of active-feedback tracking microscopy.[3, 19-26] Active-feedback microscopy presents a unique opportunity to demystify hydrogel microstructures along larger spatial, especially axial, scales with greater detail. Instead of taking images sequentially, active-feedback tracking microscopy uses modified detection[27] or patterned excitation[28, 29] to obtain real-time localization information of rapidly diffusing particles and uses a closed feedback loop to "lock" the particle in the center of the observation volume. Active-feedback tracking microscopy uses previous particle position and updated photon information for real-time location estimation; thus, by using information from prior localizations, fewer photons are required for better spatial and temporal resolution compared to image-based methods. Also, the typical excitation or detection module is three-dimensional. It is not required to take images at multiple planes and assemble them into a stack (z-stacking) for tracking along the axial direction, which greatly enhances the sampling rate for 3D tracking. Similar to active-feedback microscopy, PSF engineering techniques can also achieve high volumetric sampling rates by encoding axial information into a single 2D image. However, these approaches typically operate in widefield or epifluorescence illumination modes, where the entire sample volume is illuminated. In scattering media such as hydrogels, this broad illumination can result in increased PSF distortion due to scattered excitation and emission photons. In contrast, most active-feedback tracking methods utilize confocal or point-scanning architectures, which restrict excitation and detection to a small focal volume, thereby reducing PSF distortion and enhancing robustness against scattering-induced degradation.

Here, we used 3D Single-Molecule Active-feedback Real-time Tracking (3D-SMART) microscopy to monitor the three-dimensional dynamics of nanoparticles within agarose gels (AG) with high spatiotemporal resolution and long tracking duration. Notably, in larger nanoparticles and higher concentration AG preparations, it is frequently observed that particles can repeatedly

"hop" between confinement cages or explore the interior of hydrogel in a hopping diffusion manner. Kinetic parameters, such as the lifetimes, on/off rates, and hopping energy barriers can be extracted from highly sampled trajectories. The highly sampled trajectories depicted the complex 3D environment and could be utilized to probe the microstructures with super-resolution of ~ 10 nm.

RESULTS

High spatiotemporal SPT via 3D-SMART

Agarose gels (AG) were chosen as the model system for this work due to their extensive use in biomolecule separations and thorough characterization.[30] Fluorescent nanoparticles of different sizes were premixed within agarose gels of desired concentrations. High-speed single-particle tracking was accomplished by 3D-SMART microscopy as previously described (Fig. 1, fig. S1).[28, 31, 32] Briefly, a 3D scanning volume of 1 × 1 × 2 μm in XYZ was generated laterally with a pair of electric-optical deflectors (EODs, ConOptics, M310A) and axially with a tunable acoustic gradient (TAG, TAG Optics, TAG 2.0) lens.[33] The lateral plan is a 5 × 5 grid sampled at 20 μsec per spot, while the focus is simultaneously scanned at 70 kHZ in Z. The photon arrival information was captured by a single photon counting avalanche photodiode (APD, Excelitas, SPCM-ARQH-25) and applied to estimate the real-time position of the particle with an assumed Gaussian density Kalman filter.[34] The real-time position estimation was used to drive the piezoelectric stage to 'lock' the diffusing particle in the center of the scanning volume.

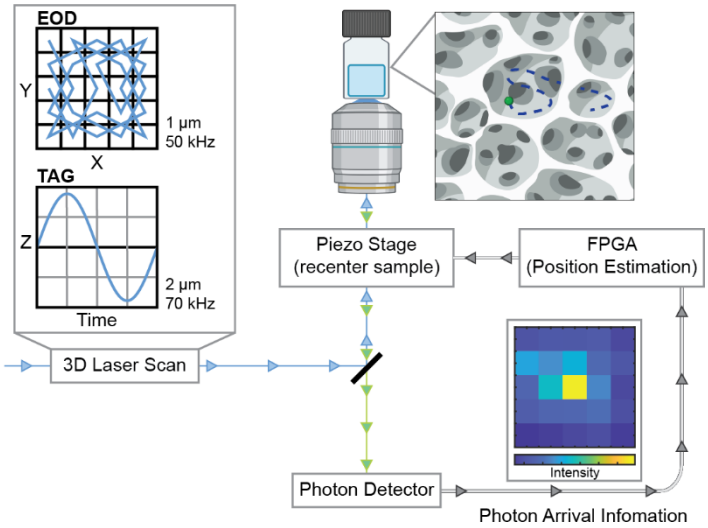

Figure 1. Illustration of performing SPT in hydrogels using 3D-SMART. A sub-millisecond 3D scanning volume of 1×1×2 μm is generated by a pair of EODs and a TAG lens. Probes were premixed with the desired concentration of agarose gel solution and solidified in the chamber. The photon detector (APD) collects the emitted photons, and photon arrival information is routed into an FPGA for real-time position estimation of the diffusing probe. The updated localization information is used to drive the piezoelectric stage to effectively hold the diffusing nanoparticle in the center of the laser scan.

The position sampling rate of 3D-SMART is 1 kHz, corresponding to the piezoelectric stage's response time. The lateral localization precisions are about 10 nm with 300 kHz intensity (i.e., 300 photons in 1 ms bin time, fig. S2a-b). Compared to non-gel tracking, the axial tracking localization precision (29.7 ± 2.8 nm) in AG was slightly reduced due to scattering in the gel network (fig. S2c). In addition to the 1 kHz position sampling of 3D-SMART, the photon arrivals can be assembled into an image called the "EOD Image." The EOD image is a critical piece of information that allows confirmation that trajectories arise from a single particle (fig. S3, also see Methods section for more details).

Particle diffusion is hindered by concentrated hydrogel and large particle size

First, passive diffusion of fluorescent nanoparticles of various sizes within the agarose gel of different concentrations was observed (see Methods). The results and tendencies were very intuitive and similar to expected and previously reported results. [30, 35] For probes of the same size, the degree of spatial confinement increased with increasing agarose concentration, leading to more hindrance of the particle diffusion (Fig. 2A, fig. S6a-c). While for the same agarose gel, the larger beads tend to be more confined while smaller beads diffuse freely (Fig. 2B, fig. S6d-f). Trajectories could be quantified using diffusion coefficient (D), power exponent α, and packing coefficient (Pc).[36] Please refer to Supplementary Information for details.

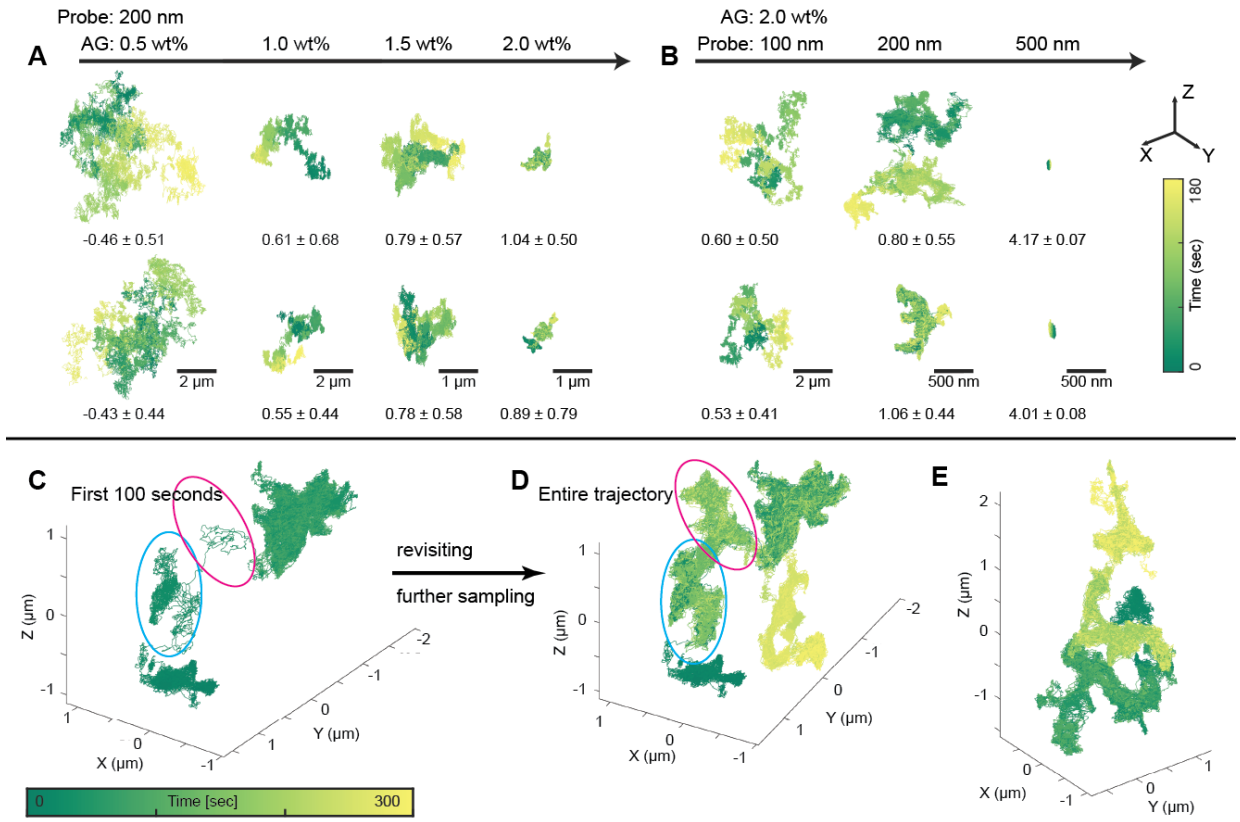

Figure 2. Meshsize- and probe-size dependent diffusion. (**A**) Representative trajectories of 200 nm probes diffusing in increasing wt% AG (see detailed information in fig. S4. N = 51 and 31 for control groups of free and fixed respectively. N = 59, 52, 127, and 93 for 0.5, 1.0, 1.5 and 2.0 wt% AG, respectively). Scale bars: 0.5 wt% and 1.0 wt%: 2 μm; 1.5 wt% and 2.0 wt%: 1 μm. (**B**) Representative trajectories of probes of different sizes diffusing within 2.0 wt% AG (see detailed information in fig. S5. N = 141, 127, and 57 for 100, 200, and 500 nm probes, respectively). Scale bars: 100 nm probes: 2 μm; 200 nm and 500 nm probes: 500 nm. All trajectories in (**A**) and (**B**) share the same colorbar and axis. (**C** and **D**) the first 100-second segment and the entire trajectory of a 200 nm probe diffusing within 2 wt% AG. The red and blue circles highlight two cavities were initially bypassed but eventually revisited after multiple hopping events. (**E**) Another example of a 200 nm probe diffusing within 2 wt% AG covering a relatively large 3D volume. The same colorabar from (**C**) applies to all three plots (**C**-**E**).

Presumably, as the particle size approaches the pore size, particles exhibit more confined diffusion. In some cases, probes dwelled in or repeatedly visited the same confinement pore. For 200 nm probes, when the AG concentration reached 1.0 wt%, hopping diffusion started to be observed: particles underwent confined diffusion in one area and intermittently escaped to neighboring areas through connective channels. Hopping escapes between two confinements always featured larger displacement and were highly one-dimensional, in contrast to confined

diffusion (fig. S7b-c). Various diffusive behaviors were observed after hopping events. Some particles hopped to relatively free diffusion (see examples in fig. S4b), while others hopped to a neighboring pore and exhibited confined diffusion (see examples in fig. S4c-d). With the combination of larger particles and denser AG, e.g., 2 wt% AG and 200 nm probes, hopping diffusion became a major diffusion pattern for particles to explore the porous hydrogel passively.

Due to the 3D nature of hydrogels, the ability to resolve diffusion and confinement structures in 3D is critical. In active feedback tracking microscopy, particles can be tracked across an ample axial range without sacrificing spatial or temporal resolution. An example of 3D pore-to-pore hopping diffusion is depicted in Fig. 2C-D (see also fig. S8a-b and movie S1), in which the particle hopped through four major cavities in a nonconsecutive manner. After being trapped in the first pore for ~ 25 seconds, the particle bypassed two cavities briefly and thoroughly explored the fourth cavity first. However, the particle swung back eventually, further sampling the second and third previously ignored confinements. Another example trajectory (Fig. 2E, see also fig. S8c-d and Movie S2) shows that hopping diffusion also occurs across a wide axial range, posing challenges to conventional tracking methods to capture and resolve. The ability to track and resolve 3D spatial information is critical when tracking smaller probes in looser meshes due to increased diffusivity.

Thermodynamics of hopping diffusion

The high sampling rate and precise localization of 3D-SMART enabled analysis of the thermodynamics and kinetics of hopping diffusion and characterization of 3D structure in AG beyond what is possible with traditional SPT. Extraction of the 3D nanoscale structure is required to determine the underlying thermodynamic within heterogeneous and porous materials. To that end, confinement pockets of diffusing particles were identified and segmented based on the dwell time in each pixel (2D) or voxel (3D) (see Methods for details). For example, as shown in Fig. 3, a 180-second 3D trajectory of a 200 nm probe diffusing within 2.0 wt% AG (Fig. 3A) was binned into 10×10×20 nm voxels (XYZ, determined by 3D localization precision). This 3D binned data was then converted into a 3D heatmap representing the dwell time within each voxel. The 3D hotspots in the heatmap correspond to the confinement pockets where the particle repeatedly visited and dwelled. Based on the intensity of the heatmap, the voxels were grouped, allowing the identification of four distinct confinements of different shapes and sizes (Fig. 3B). The volume of

the confinement was then calculated from the number of voxels, while the dwell time for each confinement was calculated from the number of localizations within a confinement.

To better understand the thermodynamics of hopping diffusion, we analyzed the relationship between fractional dwell time and fractional confinement volume. Fractional dwell time was calculated as the dwell time in each confinement divided by the total dwell time across all confinements within the trajectory. Fractional confinement volume was similarly defined as the volume of each confinement divided by the total volume of all confinements. Three experimental setups were analyzed: 200 nm probes in 1.5 wt% AG, 200 nm probes in 2.0 wt% AG, and 100 nm probes in 2.0 wt% AG. In all cases, a clear one-to-one relationship between fractional dwell time and confinement volume was observed (Fig. 3C), indicating that hopping diffusion is governed purely by entropic differences between the pores (see Methods for details), which is determined by pore size. Furthermore, this relationship suggests that the free energy difference, ΔF, between two adjacent confinements is proportional to the ratio of their confinement volumes:

$$\Delta F = -k_B T \ln\left(\frac{V_2}{V_1}\right) \tag{1}$$

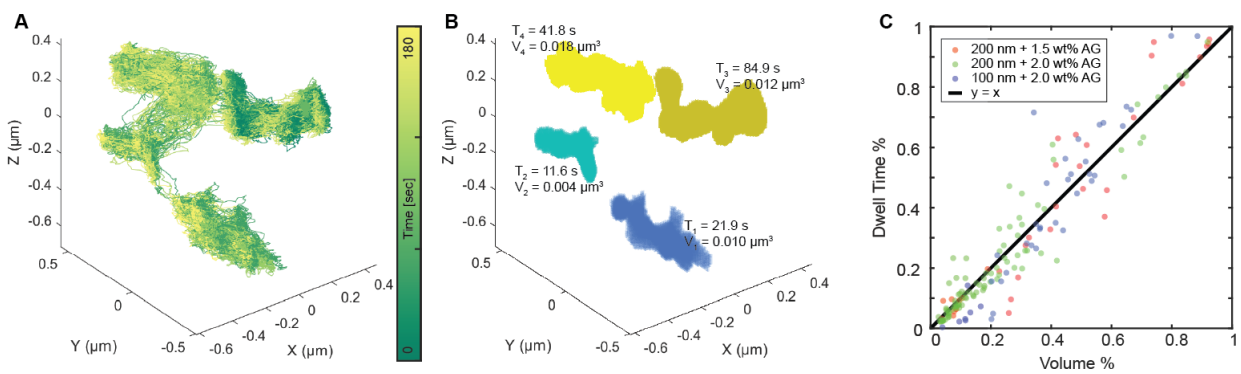

Figure 3. (**A**) 3D trajectory of a 200 nm probe's hopping diffusion within 2.0 wt% AG. Trajectory is color-coded by time. (**B**) Four identified confinements of the trajectory shown in (**A**), with corresponding dwell time (T) and confinement volume size (V). The color code represents different confinements. (**C**) Plot of the fractional volume against the fractional dwell time, indicating hopping diffusion is driven by entropic differences between confinement areas.

<u>Kinetic information extracted from hopping events</u>

Although there exist some prior experimental observations of hopping diffusion, kinetic and thermodynamic information, such as the free energy barrier, remains very challenging to extract due to the limitation in spatiotemporal resolution.[14, 37, 38] Moreover, multiple factors, including the particle diameter, size of the channel, and length of agarose polymers occupying the channel, may determine the free energy barrier the particle needs to hop from one pore to another.[39, 40] The heterogeneous nature of the agarose gel makes it challenging to probe the energy barrier from hopping diffusion in typical single-particle trajectories. Trajectories collected by 3D-SMART have the advantage of having high spatiotemporal precision, enabling frequently sampled and precise trajectories that can map out the entire environment of the particle, given a suitable duration of observation. Using 3D-SMART, it was observed that particles could hop between two adjacent pores repeatedly, allowing for a thorough sampling of the channel between the pores (Fig. 4A-B, see also Movie. S3). The tracking performance during hops was examined to exclude artifacts (fig. S9c). From these trajectories, it is possible to gain a detailed understanding of the geometry of both the pores and the connecting channels and enable a detailed analysis of the kinetics of hopping diffusion.

To better analyze these hopping events, the confinement pockets of each 3D trajectory were identified using the algorithm mentioned above in both 2D and 3D. A 2D heatmap (density of the probe centroid localizations) is shown in Fig. 4E and also serves as an indirect visualization of the interior microstructures carved out by the particle trajectory. Transitional localizations between two cavities were specifically extracted to measure the width of the "channel" connecting two pores and to measure the kinetics and thermodynamics of hopping events through these channels. The channel shown in Fig. 4E is very narrow and only 68.0 ± 3.3 nm (Calculated as 3 × std representing ~86% of the datapoints, fig. S9a-b) wider than the probe. Based on the intensity on the heatmap, the localizations of two states can be labeled accordingly as pores 1 and 2, with volumes of 0.012 ± 0.0010 and 0.009 ± 0.0008 μm^3 (2D area size: 0.092 ± 0.0002 μm^2 and 0.048 ± 0.0001 μm^2, respectively (Fig. 4F). Although their trajectories appeared relatively unremarkable along the axial dimension, the projected 2D area sizes of each confinement were 0.092 μm^2 and 0.048 μm^2, with a ratio of 1.9 (compared to the volume ratio of 1.3). This discrepancy may lead to an inaccurate estimation of the thermodynamic barrier. The translocation rate between the two confinements was also calculated as the inverse of lifetimes in each confinement (Fig. 4F, fig. S9d-e), which were 0.231 ± 0.050 and 0.227 ± 0.048 s^{-1}, respectively.

MSD analysis (2D MSD: Fig. 4C; 3D MSD: fig. S10) reveals several different diffusion states for hop events. The particle first explored the cavities freely with exponent $\alpha \approx 1$ for the first ~ 40 ms. After this free diffusion regime, the particle motion became subdiffusive with the MSD proportional to the square root of lag time up until ~3 sec. After the probe thoroughly explored the pores, the MSD fluctuates around a maximum value 0.18 ± 0.02 μm^2 (calculated based on MSD value after 3.2 sec), corresponding to a gyration diameter of 0.85 μm (0.94 μm for 3D). This gyration diameter provides a rough estimate of the area explored by the entire trajectory but may be less informative for irregularly shaped trajectories like the one presented here. Indeed, this value does roughly agree with the combined gyration diameters of the individual pores, which were ~1.02 μm in 2D or ~0.88 μm in 3D, respectively.

Hop events between pores are very short duration (~ 6 ms, fig. S7a), highly one-dimensional along the channel (fig. S7b-c), and show slightly larger displacements (13 [8, 18] nm in pores, 19 [13, 27] nm channel, Median [Q1, Q3], Kruskal-Wallis Test, $p < 0.001$, Fig. 4D). We further compared the displacement of unsuccessful hops, in which particles entered the channel but failed to pass through. These unsuccessful hops exhibited smaller displacements (11 [7, 16] nm, median [Q1, Q3], Kruskal-Wallis Test, $p < 0.05$) compared to diffusion in the pores (Fig. 4D). This result suggests the presence of an entropic energy barrier that regulates hopping diffusion, and that larger displacements may facilitate successful translocation events. A more detailed discussion of this interpretation is provided in a later section.

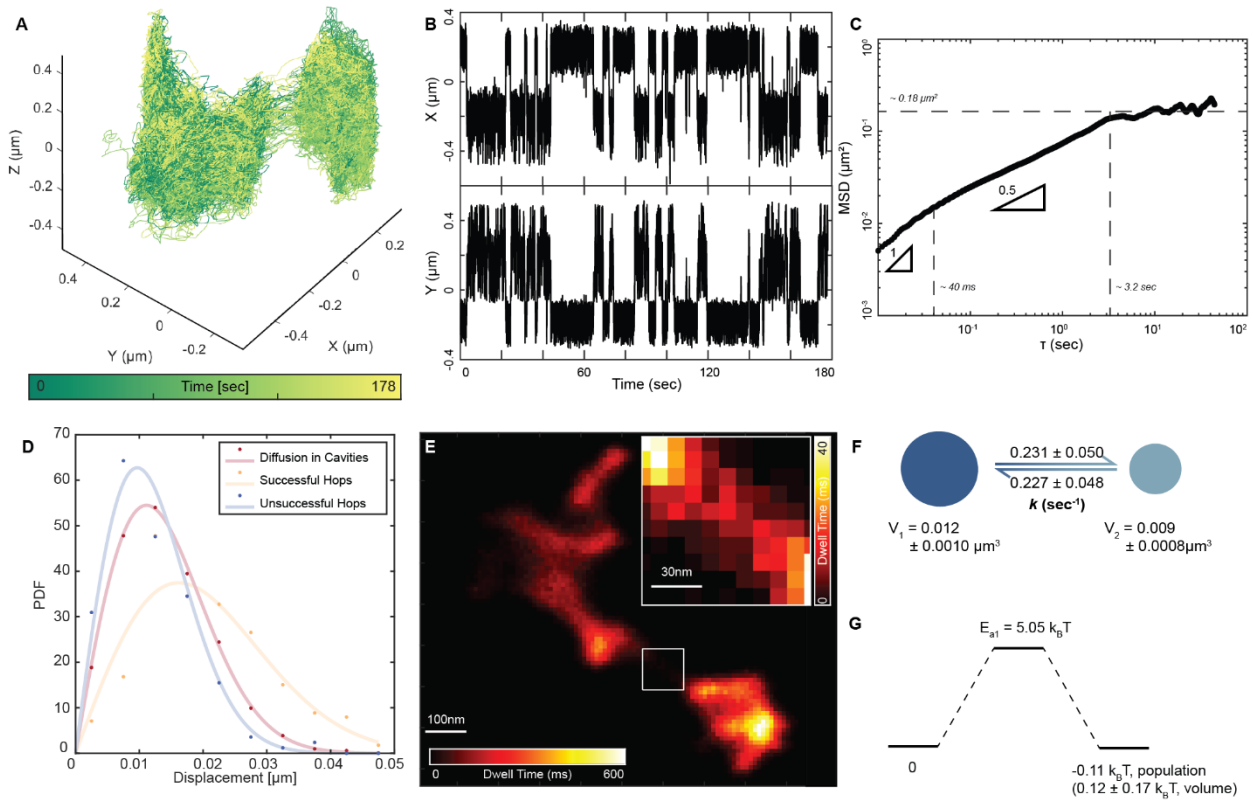

Figure 4. Illustration of a hop event. (**A**) Representative trajectory of hopping events between two cavities. NP size d = 200 nm, AG concentration c = 1.5 wt%. (**B**) X and Y traces of the trajectory shown in (**A**), indicating there existed two states for particle diffusion. (**C**) 2D MSD plot of the representative trajectory shows different diffusive states in cavities connected by a channel (minimum lag time of 10 ms). The two slopes were calculated based on a linear fit within the corresponding time window. Lag times shorter than 10 ms were chopped. see 3D MSD plot in fig. S10. (**D**) 100ms-Displacement distribution of diffusion in cavities, successful hops, and unsuccessful hops, respectively. Distributions were overlayed with Rayleigh distribution fitting. (**E**) 2D heatmap converted from 3D trajectory based on the number of localizations (or dwell time) within each pixel (10×10 nm). Inset: a zoomed-in view of the channel connecting two cavities. (**F**) Translocation rates, volumes, and areas of two confinements. (**G**) Energy diagram of the energy barrier between two confinements and the activation energy of the hop.

The free energy difference between two confinements, ΔF, and the activation energy of hop events, E_a, may be calculated based on the population within the cavities via the Boltzmann distribution:

$$\Delta F = -k_B T \ln\left(\frac{N_2}{N_1}\right) \tag{2}$$

$$E_{a1} = -k_B T \ln(\frac{N_{Ch}}{N_1}) \quad (3)$$

where N_1 and N_2 are the population of the two cavities, and N_{Ch} is the population of the channel. The calculated activation energy to hop from pore 1 was 5.05 k_BT, and the free energy difference between the two larger pores was -0.11 k_BT (Fig. 5G). The free energy difference between the pores was also calculated based on the volumetric ratio using Eq. 3, which gave a similar result (+0.12 ± 0.17 k_BT, Fig. 5G). The relatively small energy barrier between the two confinements explains the similar translocation rate between the two cavities.

It is worth emphasizing that hop events occur rapidly (~6 ms), and cannot be observed by existing SPT microrheology methods. The population of trajectory points and the energy barrier for hopping diffusion can only be measured by methods with high spatiotemporal precision.

The activation energy and kinetic rates can be further used to interpret the frequency of attempts using the Arrhenius equation:

$$k = Ae^{-\frac{E_a}{k_B T}} \quad (4)$$

in which the frequency factor A corresponds to the frequency of attempts to cross the channel. The frequency factors for transitions from pore 1 to 2 (A_1) and from 2 to 1 (A_2) are identical at 1.17 s^{-1}. Given the 1 kHz sampling rate of the trajectories, this can be translated to 0.117 % of trajectory localizations within each confinement that can be considered attempts at crossing the narrow channel. This attempt frequency can be translated to a distance from the opening of the channel. To determine the distance from the channel that a particle must be to attempt a hop, we examined the cumulative probability of observing a trajectory point as a function of distance from the channel (Fig. 5A). It can be found that the distance at which the cumulative probability reaches 0.117% occurs at 15 nm from the channel for pore 1, and 18 nm from the channel for pore 2, noticeably close to the step size of diffusion within the confinement (13 [8, 18] nm, median [Q1, Q3]). The difference between these attempt distances may reflect difference channel geometries on either side.

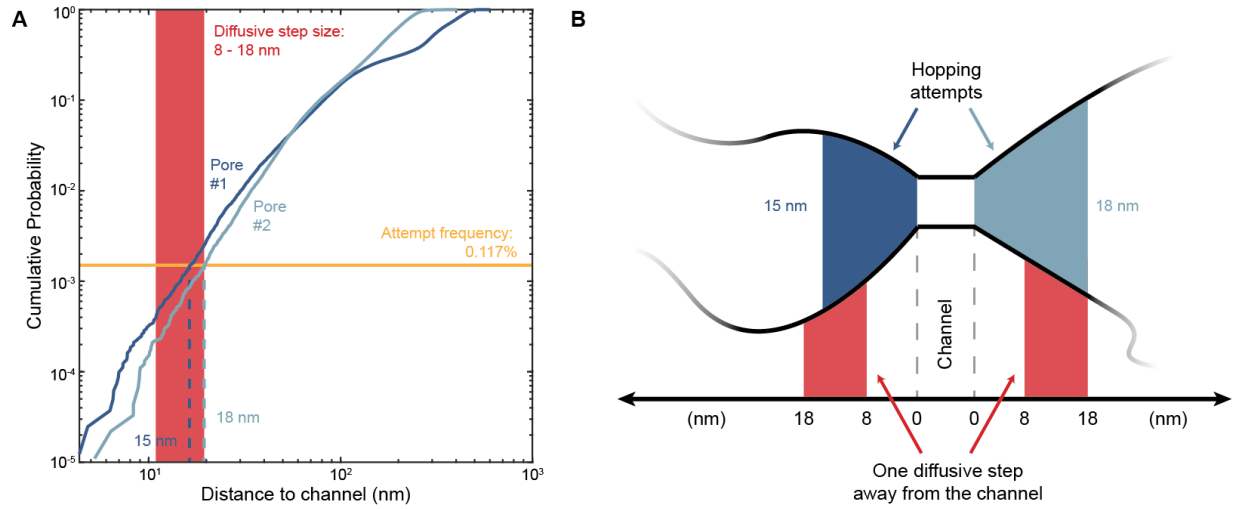

Figure 5. (**A**) Cumulative distribution function (CDF) of particle localizations as a function of distance to the channel for pore 1 and 2. The solid yellow line indicates the 0.117% cumulative probability corresponding to the frequency factor of 1.17 s^{-1} with 1 kHz sampling. The corresponding distance for hopping attempts is 15 nm and 18 nm for confinement 1 and 2, respectively, as noted by the blue lines. (**B**) Illustration showing hopping starts to attempt roughly one diffusive step away from the channel.

The measurement of free energy differences and energy barriers can be applied to more complex hopping diffusion scenarios involving multiple connected cavities, by identifying the interconnected cavities and analyzing particle occupation. The trajectory shown in Fig. 3A-B was used as an example, and the resulting energy landscape is presented in Fig. 6A. Building upon this example, we applied the same measurement approach to a larger dataset of 200 nm probes diffusing within 2.0 wt% agarose gel (characterized from 78 hop events across 18 trajectories of 93 total, Fig. 6B).

The free energy barrier involved in hopping diffusion can be explained by different frameworks, including the concept presented in "hopping diffusion"[37-39] and "diffusive escape".[40] Prior work on hopping diffusion within gel networks describes the fluctuation of a gate between two neighboring confinements, which could allow a particle with size exceeding the network mesh size to hop into a neighboring confinement. In this case, the channel represents the polymer chain fluctuation of the gate, while its volume represents the number of microstates. Based on this hopping diffusion model, the activation energy barrier is given by

$$E_a = k_B T (d/a_x)^2 \tag{5}$$

where d is the particle size, and a_x is the length of the polymer network. Based on this equation, the hopping energy barrier of 200 nm probes within 2.0 wt% AG (Fig. 6B) can be used to probe the length of polymers within the network. The energy barriers calculated based on particle occupation of the channel results in a calculated network length scale of 130 [107, 181] nm (Median [Q1, Q3], Fig. 6C), which is consistent with expected length of 50 nm to >200 nm for 120 kDa agarose.[41, 42] While agarose is a highly heterogenous system, the experiments presented here are a good starting point to understand hopping diffusion in more controlled polymer networks and synthetic films with known (or unknown) structure.

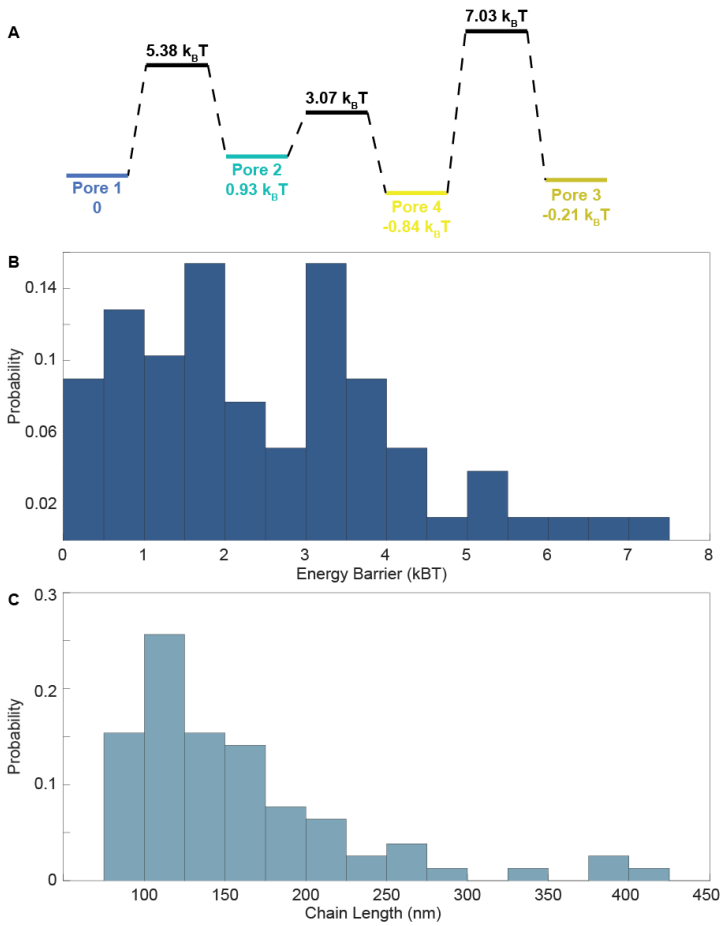

Figure 6. (**A**) Example of free energy lanscape measurement of hopping diffusion across multiple connected cavities, using the trajectory shown in Fig. 3A-B. The font color is corespond to cavities identified in Fig. 3B. (**B**) Distribution of hopping diffusion free energy barrier of 200 nm probes in 2.0 wt% AG. 78 hops were characterized across 18 trajectories that included hopping events (of 93 trajectories total). (**C**) Distribution of of chain length calculated via Eq. 5 from the free energy barriers shown in (B).

"Diffusive escape" describes Brownian particle escape from confinement through a nanochannel and is usually probed with specially synthesized films, such as a liquid-filled inverse opal film.[40, 43] In the diffusive escape model, the narrow channel itself effectively acts as a free energy barrier, owing to its limited size, as well as additional repulsive potentials that may prevent translocation through the channel. From the current data, if one assumes that the channel exists physically and is rigid, it is possible to estimate the channel volume based on the localization within the channel by $V \simeq 2\mathrm{std}(x) \times 2\mathrm{std}(y) \times 2\mathrm{std}(z)$ (± 1 σ, containing ~ 68% of the data), which gives a result of 5.28×10^5 nm^3. Plugging that the volume size of pore 1 (0.012 ± 0.0010 μm^3 calculated above) into Eq. 3 yields an estimated activation barrier of 3.20 ± 0.09 k_BT, which is significantly lower than the value of 5.05 k_BT obtained above from localizations within the channel. The discrepancy between these two values indicates that an additional energy barrier exists, in addition to the entropic barrier from the limited channel size. This suggests the presence of additional repulsions that hinder translocation beyond the effect of geometry. Notably, this extra barrier appears to be specific to narrow channels, as larger pores exhibit energy differences dependent solely on their volume. This additional obstacle could stem from the hopping diffusion model discussed above, where polymer chain rearrangement introduces an additional energy barrier. Another possible factor is the electrostatic repulsion between negatively charged particles and the negatively charged gel microenvironment, which would be most pronounced at the interface between channel and pores.

CONCLUSION

In this work, we have demonstrated that active-feedback single-particle tracking methods have great potential for microrheology studies, providing highly spatiotemporally resolved 3D information. The combined high sampling rate, 3D localization, and long duration of observation allowed for the complete characterization of nanoscale confinements and channels within heterogeneous agarose gel networks. Although hopping diffusion has been previously reported, this work, for the first time, quantitatively characterizes the duration of hopping events and extracts free energy barriers directly from single-particle trajectories. The direct observation of these hopping events between two adjacent nanoscale pores presents a unique opportunity to understand narrow escape events in hydrogel networks. Furthermore, the high spatiotemporal resolution of

each single-particle trajectory also serves as structural probes, mapping the interior microstructure of 3D porous materials in detail (Fig. 3D).

This work also demonstrates the broader potential of active-feedback tracking for probing transport and structure in a wide range of soft and heterogeneous materials. This technique will also present new avenues to study the penetration of virus or drug delivery cargo through mucus or mucin hydrogels,[44, 45] interpreting the microscopic view of particle dynamics during gel electrophoresis or column chromatography,[12, 46] exploring the mechanism behind critical material chemistry, such as self-healing and catalytic processes,[47, 48] and illustrating the dynamics within biomolecular condensates[49].

METHODS

Sample preparation

Agarose powder (type I low EEO, Sigma-Aldrich) was mixed with 1× Tris-Acetate-EDTA buffer (Apex Bioresearch Products, 18-134L) in a microwaveable flask and microwaved until the agarose was completely dissolved without overboiling. Cool down the agarose solution down to about 60 °C in water bath. 100 nm, 200 nm, or 500 nm carboxyl-functionalized polystyrene microspheres (Bangs Laboratories, Inc., FCDG002, FCDG003, or FCDG005) were pre-diluted in distilled water and pre-warmed to about 60 °C in water bath. The anionic carboxyl group on the emitter beads would be expected to have minimal interaction with the anionic agarose.[50] Also, it was demonstrated that premixing probes with agarose gel has no significant impact in gel formation.[30] Equal volume of agarose solution and microsphere dilution were quickly mixed to achieve the desired final concentration. 300 μL of mixture was transferred into a chambered coverslip (Ibidi, 80826). The sample was solidified under room temperature for about 15 minutes and 100 μL distilled water was applied on the top of gel to prevent dehydration.

Validating the tracking of an individual particle

As part of the 3D-SMART mechanism, the EOD continuously scans the particle in a 5×5 grid. The result is a real-time "EOD image" which can be used to evaluate tracking performance. If only one individual particle is being tracked, the center pixel of the EOD image will have most photon counts. If more than one particle exists in the scanning plane, multiple photon-count maxima will exist in a single EOD image, which is also accompanied by an increase in the average particle

intensity. These two factors can be used to rule out trajectories containing multiple particles. An example of the system tracking more than one particle is shown in the Supporting Information (fig. S3).

Cavity identification

For 2D cavity identification, trajectories were processed using a sliding window of 180 second window, stepped in 30-second increments. Particle localizations were distributed into 10×10 nm^2 pixels, selected based on the localization precision. The density of localizations in each pixel is convoluted with a 3×3 Gaussian Kernel. Pixels with fewer than 15 localizations were filtered out. Areas were grouped using the `bwconncomp` function in MATLAB. Areas in different segments were merged to form the final result. Areas with fewer than 60 pixels were excluded. This threshold was determined by observing fixed particles.

Similarly, in 3D cavity identification, trajectories were processed using a sliding window algorithm, with 180-second window size and 30-second step size. Particle localizations were distributed into voxels with the size of 10×10×20 nm in XYZ, determined by localization precision. The localization density in each voxel is convoluted with a 3×3×3 Gaussian Kernel. Voxels with fewer than 2 localizations were filtered out. Volumes were grouped using the `bwconncomp` function in MATLAB. Volumes in different segments were merged to form the final result. Final volumes with fewer than 300 voxels were excluded. This lower threshold was determined from trajectories of fixed particles. The volumetric images were plotted with the `vol3d` function.[51]

The pixel/voxel number within each isolated area/volume represents the cavity area/volume size, while numbers of particle localizations within the area/volume represent the dwell time within the area/volume. Measuring uncertainty of the area/volume size is calculated by expanding or shrinking the area/volume by one pixel/voxel.

Position categorization

Positions were categorized based on their spatial relationship to cavities. Positions labeled as 'not-in-cavity' were further classified as follows:

Successful hop: Consecutive positions labeled 'not-in-cavity' that connect two distinct cavities were registered as 'successful hop', indicating pathways or connections between cavities.

Unsuccessful hop: The rest of the consecutive positions labelled 'not-in-cavity' and located within the channel were registered as 'unsuccessful hop', indicating events of particle entering the channel but not successfully pass through.

Measuring uncertainty: All remaining 'not-in-cavity' positions that do not connect cavities are near cavities but lack sufficient sampling to be definitively assigned to any specific cavity. These positions represent 'measuring uncertainty'. For both thermodynamic and kinetic analysis, these uncertain positions were ignored.

<u>Fractional dwell time equals fractional confinement volume</u>

For diffusing particle constituting isolated states with total volume of V_{tot} and total dwell time of t_{tot}. For each individual state with volume of V_k and dwell time of t_k, according to the partition function, the fractional dwell time is

$$t_k\% \simeq \frac{e^{-F_k/k_BT}}{\sum_i e^{-F_i/k_BT}} \tag{6}$$

in which, F_k the thermodynamic potential energy. In this scenario, the thermodynamic potential is simply contributed by entropy, $F = -ST$, which can be determined using Boltzmann's entropy formula:

$$S = k_B \ln \Omega \tag{7}$$

in which, k_B is Boltzmann's constant, and Ω is the number of microstates within macrostate. Therefore, the fractional time can be written as

$$t_k\% \simeq \frac{e^{S_k/k_B}}{\sum_i e^{S_i/k_B}} = \frac{\Omega_k}{\Omega_{tot}} \tag{8}$$

For the isolated confinements constituted by diffusing particles, Ω is proportional to the volume of confinements, V. Naturally, we have the fractional dwell time equal to the fractional confinement volume.

$$t_k\% \simeq \frac{\Omega_k}{\Omega_{tot}} = \frac{\mathrm{V}_k}{\mathrm{V}_{tot}} = V_k\% \tag{9}$$

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Y.L. and K.D.W. conceptualized the study. Y.L. and K.D.W. were responsible for the methodology. Y.L. and H.L. performed investigations. K.D.W. was responsible for funding acquisition. Y.L., H.L., and K.D.W. curated the data. Y.L., H.L., and K.D.W. performed the visualization. Y.L. and K.D.W. wrote the original draft and reviewed and edited the manuscript. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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