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Optical-tweezer-induced microbubbles as scavengers of carbon nanotubes

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Abstract
A modified optical tweezers set-up has been used to generate microbubbles in flowing, biologically relevant fluids and human whole blood that contains carbon nanotubes (CNTs) using low power (\(\leq 5\) mW), infrared (1064 nm wavelength), continuous wave laser light. Temperature driven effects at the tweezers’ focal point help to optically trap these microbubbles. It is observed that proximate CNTs are driven towards the focal spot where, on encountering the microbubble, they adhere to it. Such CNT-loaded microbubbles can be transported both along and against the flow of surrounding fluid, and can also be exploded to cause fragmentation of the bundles. Thus, microbubbles may be used for scavenging, transporting and dispersal of potentially toxic CNTs in biologically relevant environments.

Online supplementary data available from stacks.iop.org/Nano/21/245102/mmedia

(Some figures in this article are in colour only in the electronic version)

1. Introduction
Carbon nanotubes (CNTs) have a myriad of applications in diverse fields. In medicine [1, 2] CNTs, with therapeutic molecules attached to them [3] or encapsulated within them [4, 5], have been envisioned as directed drug deliverers [6], gene carriers [7], contrast agents in imaging [8], nano-ablators [9] and \textit{in situ} biosensors [1, 2]. Studies have established the efficacy of CNTs in these tasks: the same amount of drug, when attached to CNTs, produces a greater effect [10] as CNTs can permeate cellular membranes with ease [3, 11]. However, there are growing toxicity concerns. Studies \textit{in vitro} and in rodents reveal harmful effects of CNTs on different types of cells [12–16], leading to the question: do the benefits of CNTs as directed drug deliverers outweigh the harm they may possibly cause? Once the primary role of CNTs is fulfilled, it is, therefore, desirable to promote the rapid removal of CNTs from the body, or the dispersal of aggregated clusters to sub-micron size [14, 15, 17] in order to mitigate the harmful effects. We demonstrate, using a flow-cell married to an optical tweezers set-up that simulates physiological conditions, the use of microbubbles to accomplish both these tasks. Created and manipulated by tightly focused laser light, microbubbles are shown to act as scavengers of CNT bundles flowing in biologically relevant fluids, enabling subsequent easy removal or dispersal.

Recent experiments [18] in suspensions of single-walled carbon nanotubes (CNTs) in optical tweezers have demonstrated (i) the repulsion of CNTs from the tweezer focus, (ii) the formation of microbubbles upon photothermal excitation of CNTs and (iii) the subsequent trapping of these microbubbles at the tweezer focus. Interestingly, the microbubbles were found to attract bundles of proximate CNTs [18, 19] and carbon particles [20]. These observations have prompted us to substantially extend this earlier work. In the present study we have examined (i) the formation of microbubbles in a variety of biologically relevant fluids, including human whole blood, (ii) the adhesion of proximate CNTs onto the bubbles, (iii) the optical micromanipulation of the cargo-laden bubbles through the fluid, and (iv) dispersal of CNT bundles by controlled explosion of CNT-encrusted microbubbles. We present results of CNT trapping in fluid flow, where scavenging action is demonstrated by collecting CNTs onto an optically trapped microbubble and then moving the CNT-encrusted bubble both along and against the flow. We also demonstrate shattering of a large cluster of CNTs.
Figure 1. (a) Schematic depiction of the experimental apparatus in which a fluid flow-cell is incorporated into an optical tweezers set-up. (b) Multiple microbubbles formed upon absorption of 1064 nm light by CNT bundles. (c)–(e) Formation of microbubbles and the attraction of a proximate CNT bundle towards the tweezer focal volume. Each of the frames is temporally separated from the preceding one by 40 ms. These snapshots were taken under static conditions wherein the fluid velocity in the flow-cell was zero. The bright patch at the junction of two bubbles is due to laser light scattered from the CNT bundle at the laser focus.

2. Materials and methods

Single-walled CNT bundles suspended in a variety of physiologically relevant fluids (water, saline (300 mOsm), bovine serum albumin (2% w/v) and agarose (0.01% w/v)), each with different viscosity, were studied. The CNTs were 1.2–1.5 nm in diameter and 2–5 μm long. All the solutions used in our experiment were filtered by a 0.2 μm filter to avoid impurities and the CNTs were subsequently added. Viscosities were measured using an Ostwald’s viscometer; the measured values bracketed and exceeded the mean viscosity of human blood.

The experiments reported here were carried out using an optical tweezers set-up incorporating a fluid flow-cell [24] which simulated the physiological environment where the technique may find application. A schematic representation of the experimental assembly is depicted in figure 1. The flow-cell that we used has dimensions 5 cm × 5.5 cm × 200 μm. A syringe pump was used to pump various fluids through this flow-cell at constant throughput values over the range 0 μl s⁻¹ (representing static conditions) to 50 μl s⁻¹, the corresponding flow speeds being 0–500 μm s⁻¹. Flow speed values were experimentally quantified in a separate experiment by flowing polystyrene beads (of 2 μm diameter) suspended in the fluid under study. Real-time monitoring of the motion of the bead allowed a reliable measure of the fluid velocity.

In the present series of experiments, the laser that was used for optical trapping was a low power (5 mW), 1064 nm
wavelength, continuous wave (cw), Nd:YVO₄ laser. This was focused using a 100× objective of numerical aperture 1.3 or, when a larger field of view was desired (such as in fast flow situations), by a 60× objective of numerical aperture 0.75.

Imaging of events occurring in the vicinity of the optical trap was observed by means of a CCD camera coupled to a computer that recorded the observations in real time. These data were monitored frame by frame to measure velocities and trajectories. The interval between two consecutive frames was 40 ms. Analysis was by means of image processing software (Image J). The laser power at the focus point, just after the objective, was measured using an integrating sphere photodiode. The detector head was placed on top of the objective to collect the transmitted laser light. The powers measured ranged from 5 to 37 mW. In the experiments we observed that bubble formation occurred at power levels of ~5 mW and more, while the bursting of bubbles was observed to be efficient at power levels of 20 mW and more. The holding of bubbles was also carried out at power levels of 5 mW and more. These power levels were consistent in our experiments with different liquids.

As noted above, the experiments that we report here were carried out with single-walled carbon nanotubes (CNT). 1.5 mg of CNT was added to 15 ml of the fluid under study. The mixture was sonicated to ensure proper dispersal of the CNTs and to avoid formation of very large clumps. A small amount of this solution was placed on a thin (0.1 mm) glass coverslip and viewed through the microscope that comprises our optical tweezers set-up. The sample is visually scanned (by means of a precision translational stage) for CNT bundles, while the laser blocked. On locating a bundle, the laser is shone on the bundle. In experiments conducted under flow conditions, the liquid in the flow-cell was visualized through the microscope, and the laser was shone on a flowing CNT bundle.

In the case of experiments involving human blood, 10 ml of blood was drawn from healthy human volunteers in vials containing 90 mg of anticoagulant powder (where each gram of anticoagulant consisted of 450 mg of dextrose, 400 mg of sodium citrate, and 150 mg of citric acid). The addition of such an anticoagulant does not change the physical parameters (such as volume or viscosity) of the blood. All such experiments involving human blood were conducted in accordance with the rules and procedures adopted by the Tata Institute of Fundamental Research Human Ethics Committee. To measure haematocrit values, the collected blood was centrifuged at 0.4 g, and the volume of the pellet thus formed was noted. The fraction of pellet volume to the total volume of blood yielded the haematocrit value. It should also be noted that blood was drawn afresh at the beginning of each experiment and was stored for a maximum of 2 h before being used in the experiments.

The absorption coefficient of blood was measured by placing a cuvette filled with whole blood in the laser path. The transmitted laser light was collected using a large aperture lens and measured using an integrating sphere coupled to a photodiode. This was done in order to minimize the loss of transmitted light due to scattering. Typically, the power levels measured with the empty cuvette were taken to represent the incident power while the power levels measured with the blood-filled cuvette were taken as the transmitted power.

In the course of our measurements it also became necessary to use optical traps at multiple locations. Such multiple traps were created using a simple technique developed in our laboratory [25] using a wire mesh. In brief, an Nd–YVO₄ laser beam (1 mm diameter) was passed through a beam expander so as to produce a parallel beam of 10 mm diameter. The beam was then transmitted through two lenses that formed a telescopic arrangement, and through a 45° mirror onto a large numerical aperture 100× microscope objective (NA = 1.3). A nickel wire mesh of dimension 175 μm × 175 μm, with 95 μm wire thickness and 50% transmission, was placed in the beam path near one of the telecope lenses. The multiple beams that result from diffraction were used to trap and manipulate CNT bundles and also to form multiple bubbles in the same field of view.

3. Results and discussion

In our experiments we find that, upon exposure to very low power (≤5 mW), tightly focussed, continuous wave, 1064 nm light a profusion of microbubbles appear. Tight focusing of laser light leads to rapid creation of a large number of bubbles (figure 1) which tend to aggregate, whilst weaker focusing results in a single bubble; the sizes of these can be controlled using laser power. Bubbles that range in size from a few to several tens of micrometres are extremely stable, and are greatly amenable to optical micromanipulation. We attribute bubble formation to localized heating at the tweezer focus [18], due to the efficient absorption of near-infrared light by the CNTs. The elevated temperatures at the CNT location result in expulsion of gases (dissolved atmospheric gases) in the liquid and vaporization of the surrounding fluid. This volume of hot gas is trapped by the cooler liquid to form a bubble.

A feature that is crucial to our application is the movement of CNT bundles. The CNT bundles that are normally repelled by the tweezer [18] display the complete opposite behaviour in the presence of bubbles—they are, in this case, invariably attracted towards the tweezer focus. This too, we believe is a consequence of the extremely efficient absorption of infrared light by the CNT, which results in bubble formation as well as the creation of a localized hotspot at the tweezer focus. The associated steep temperature gradient in the fluid and the resulting steep surface tension gradient cause convection currents. Such currents, in turn, force temperature driven movement of matter [18–20] in their vicinity. It is these convective currents that propel the CNT bundles towards the focus, overcoming the dipole repulsion of the bundle [18] by the tweezer. The curved trajectories (figure 1) that are often seen support this mechanism. When a large number of bubbles exist, the bundle is seen to follow tortuous paths, avoiding other bubbles, and reaching the focus, (see supplementary video 1 available at stacks.iop.org/Nano/21/245102/mmedia), supporting the view that it is steep temperature gradients [26] rather than dipole forces that dominate.
The trajectories are less complicated when a single bubble is present, and is trapped at the focus of the tweezer: the bundles in the vicinity now move to the focus in straight-line paths. En-route they encounter the bubble surface and adhere to it. CNTs in the field of view (~100 μm) are attracted at high speeds to a bubble; they then adhere to its surface (see supplementary video 2 available at stacks.iop.org/Nano/21/245102/mmedia). CNT bundles of size 1–20 μm are attracted towards the bubble at speeds ranging from 4–67 μm s⁻¹ in agarose to 40–150 μm s⁻¹ in saline, with smaller bundles moving faster; the differences in speed in agarose and saline is merely a reflection of the differences in their viscosity, with the former being more viscous.

The bubbles, along with their load of adhered CNT bundles, could be readily moved by manipulating the position of the focal spot on the sample translation stage. Thus, single bubbles created by the photothermal excitation of CNTs are very crucial to the scavenging mechanism we propose due to the several roles they play—they confine the hot gas and help maintain a temperature gradient and are thus responsible for the convective motion of matter in the vicinity; they offer a surface onto which the CNTs adhere as they move towards the local hotspot and, finally, they provide an object that can be trapped by the tweezer and manipulated. It is this situation of single microbubble formation and CNT adhesion that we propose to utilize. We note that this is in contrast to earlier work that considered [18, 20] bubbles a hindrance to optical trapping. In our work we show that it is due to thermal effects that trapping of microbubbles can be achieved, albeit that the thermal effects are produced by optical means (absorption of optical energy).

Are bubbles only formed at CNT locations? Or do they form upon laser irradiation of any liquid medium? We have conducted experiments in which multiple optical traps are utilized to irradiate CNT bundles dispersed in liquids. Figure 2(a) shows the locations of 12 traps, of which nine are distinctly visible because of the amount of light that is back-reflected onto our CCD camera. Figure 2(b) shows CNT bundles dispersed in bovine serum albumin where, out of the different trapping locations, only three are spatially coincident with the locations of CNT bundles. It is clear from figure 2(c) that bubbles are generated only in the presence of CNT bundles; the liquid on its own does not produce bubbles.

We now examine the feasibility of single bubble formation, CNT adhesion and micromanipulation in a fluid environment that is not static but is flowing. Figure 3 is a sequence of snapshots obtained using our flow-tweezers set-up, each frame being 40 ms apart, depicting the motion of a large bundle of CNTs initially carried along the flow of the fluid (vertically downwards in the image), then being rapidly deflected sideways due to the large repulsion force as it approaches the tweezer’s focus. However, as in the static case, bundles that come sufficiently close to the focus, even though expelled, undergo rapid heating during the brief period in which they are in the focal region, so as to extrude bubbles. These bubbles are then pushed by the aforementioned temperature gradient towards the focus. At low flow rates (≤5 μl s⁻¹) fairly large bubbles (≤100 μm diameter) are formed and trapped in the focal volume. These attract CNT bundles that flow past, and are able to pull them transverse to and even against the fluid flow.

In faster flow (6 μl s⁻¹ and above), smaller bubbles (<1 μm diameter) are formed, presumably due to the better heat dissipation in the surrounding fluid. They, in turn, are less efficient in trapping bundles, which are now moving past with greater momentum. Further, the retention rate of the bubbles at the tweezer focus, and the CNT cargo at the bubble surface, are both low, as they are now subject to bombardment by flowing particles with a larger momentum and are thus easily dislodged.

The capture of a CNT bundle moving past a trapped bubble involves several effects—momentum of the bundle tending to continue motion along the flow, repulsion from the focal volume due to an optical dipole force [18], and attraction towards the hotspot. In the case of a single trapped bubble, its location and that of the hotspot coincide. So, the movement of the bundle towards the hotspot is synonymous with attraction to a bubble. As is obvious, the trapping of a
Figure 3. Snapshots showing attraction of CNT bundles towards a microbubble. The CNT bundles (circled in white) are flowing downwards (250 μm s⁻¹), in the direction indicated by the vertical white arrow in each frame. Panels ((a)–(c)) and ((d)–(h)) show attraction of CNT bundles that result in curved trajectories (see text). Each of the frames is temporally separated from the preceding one by 40 ms. Panels (i)–(k) show the transportation of a CNT-encrusted microbubble in an upward direction against the downward flow of fluid. A real-time movie showing the trajectories of CNT bundles can be viewed in supplementary video 2 (available at stacks.iop.org/Nano/21/245102/mmedia).

Figure 4. Simulated trajectories of a CNT bundle under various conditions. Each square panel represents the field of view of our tweezer set-up, with the laser focus at (0, 0). The flow is vertically downwards. The dots, which are equispaced in time, represent the trajectory of the CNT bundle. (a) Trajectories under steady flow, with no bubble at the laser focus. The CNT bundles are repelled. (b) Trajectories under steady flow at a low rate, with a bubble at the laser focus. The CNT bundles follow straight-line paths to the bubble. (c) Trajectories under fast flow conditions, depicting overshoot and capture of the CNT bundle by the bubble.

Simulations of the trajectory of CNT bundles using classical mechanics reproduce experimental results well. Our computer modelling involved the simulation of trajectories of bundles of carbon nanotubes by solving the classical equation of motion in two dimensions (the x–y plane), with the tweezer focus assumed to be located at the origin (0, 0) of the coordinate system (located at the centre of the panels shown in figure 4). The direction of fluid flow is taken to be vertically downward (towards y = ∞). The initial positions of the CNT bundles were uniformly distributed on the upper edge of each panel of figure 4. Thereafter, as the CNT bundles drifted uniformly downward, they were subject to two central forces: one is an attractive force that is directed toward the origin, representing the temperature driven inward force, and the other is a repulsive force that is directed away from the origin, signifying the dipole force. The magnitudes of both
forces increase as the bundle approaches the centre. The relative strengths of the force and the drift velocity, as well as the size of the bubble could be varied. The resulting vectorial equation of motion was solved using Mathematica.

We have assumed that a single bubble is trapped with fluid flowing at constant speed $V$; this situation is valid in the central region of the channel, away from the edges of our flow-cell. The panels in figure 4 show typical trajectories for the CNT bundles; these closely resemble those seen in our experiments: bundles closer to the axis fall directly to the centre, while those at the sides often overshoot, the extent of overshoot being dependent on the relative strength of the central force and the flow.

Thus, experiments and simulations make it clear that single bubbles, even in flowing liquids, can attract CNTs and hold them trapped. We further find from our flow-cell experiments that the bubble can be transported without dropping the adhered CNTs, both along and against the flow (figure 3).

Having demonstrated the three basic features of the proposed scavenger, namely bubble formation, entrapping of CNTs, and transportation of CNT-encrusted bubble, we now postulate how this might find utility in the removal of drug-delivering or tissue-ablating CNTs from within the body after the completion of their intended curative task. Consider CNT-aided localized drug-delivery. For CNT removal, a tapered fibre carrying infrared light is to be inserted to form a tweezer-like environment so as to induce formation of a bubble and its trapping at the focus. As we have demonstrated, this bubble will, in turn, attract and trap bundles of proximate CNTs. We recall earlier work [27] that demonstrates the trapping of micron-sized dielectric particles by microbubbles attached to the tip of a heated, metallized tip. In the present context, a CNT-encrusted bubble can be slowly retracted along with the fibre, maintaining illumination to ensure continued trapping of the bubble which, thus, acts as a scavenger and transporter. An alternative to drawing out the CNT-encrusted bubble is its in situ dispersal. It is known that CNT toxicity reduces with size [14, 15]. We show that CNT dispersal can be achieved by forming a microbubble, allowing CNTs to adhere to its surface, and ramping up the light intensity so as to burst the bubble. This fragments the adhered CNT bundles and disperses them, achieving a dramatic decrease in local CNT concentration (figure 5). The figure depicts successive frames from a real-time movie clip (separated by 80 ms) that we took in the course of a flow-cell experiment. The first frame in figure 5 shows a bubble that is coated with CNT bundles. The second frame depicts its subsequent explosion as it comes in the vicinity of the laser focus, resulting in dispersal of the surface-attached CNTs (shown in the last frame). Our measurements indicate that the bubble explodes on timescales shorter than 40 ms.

Do the dispersed CNTs eventually re-aggregate? Our dispersal experiments were conducted in a flow situation, akin to physiologically relevant flow conditions. We have observed that, even under static (zero flow) conditions, no re-aggregation of CNTs is observed for 30 min of observation time. In flow conditions, re-aggregation will be even less likely and, indeed, we found no evidence for re-aggregation within our field of view ($80 \mu m \times 100 \mu m$).

We have repeated our experiments with whole blood (haematocrit of 45%) freshly taken from a human volunteer and typical results are shown in figures 6 and 7. As is normal when handling human whole blood, a very small measure of anticoagulant powder was added to permit experiments.
without coagulation of blood. The absorption coefficient of whole blood was measured by us to be 9 cm$^{-1}$ for 1064 nm irradiation. This value appears to be in accord with results of simulations that have been reported by Barton et al [28]. In spite of this large amount of scattering, we find that bubbles do form, and we have succeeded in imaging bubble-induced dispersal of a CNT bundle in whole blood.

Does the absorption of light by a single erythrocyte compete with that by the CNT bundle? In a single RBC, haemoglobin is the cell constituent that is expected to be the major absorber of incident laser light. It has an extinction coefficient of $\sim100$ cm$^{-1}$ mol$^{-1}$ at 1064 nm [29], several orders of magnitude less than that for single-walled CNTs [30].

Figure 6 shows the formation of a bubble at one end of a CNT bundle. Proximate red blood cells (RBCs) are attracted to the surface of the bubble and form a layer which appears to shield the remaining RBCs and prevents them from ‘falling in’ towards the bubble surface. Surrounding CNT bundles (or fragments of bundles) appear to move through the intercellular spaces and thus continue to ‘fall in’ towards the bubble. The image makes clear that the very act of bubble formation does not seem to affect the morphology of the bulk of red blood cells that are not directly in contact with the bubble. Our observations indicate that the size of the bubble that is formed is affected by flow speed. In our experiments, the flow parameters were carefully controlled while, in a biomedical environment, it would be possible to determine blood flow velocities by means of techniques such as Doppler imaging [31]. Figure 7 depicts the explosion of the CNT bundle. Panel (a) of figure 7 shows a CNT bundle in whole blood. Upon exposure to focused laser light, microbubbles are created that induce explosion of the CNT bundle (panel (b)). The subsequent two panels of figure 7 (panels (c) and (d)) show dispersal of the CNTs occurring on timescales of $<40$ ms. The shapes of cells proximate to the exploding CNT bundle (beyond $\sim3$ μm) are seen to remain intact. The images indicate that there is no bulk disruption caused by the CNT dispersal that follows bubble explosion and, therefore, it appears very unlikely that the endothelial cells of the capillaries will be affected in this proposed scheme.

It is clear that, in order to reduce the localized CNT concentration (and, hence, CNT-induced toxicity), there are two different scenarios: (i) in slow-flow situations ($\leq5$ μls$^{-1}$), it appears possible to form relatively large bubbles that attract proximate CNTs. If a tapered optical fibre is inserted into the human blood flow system, it may be possible to devise a scheme wherein the CNT-encrusted large bubble is then extracted using the fibre. (ii) In faster flow situations, our results appear to indicate that it is the smaller microbubbles that would be of utility for CNT dispersal via the explosion route.

We have also considered whether the flow conditions in our experiments are of relevance to human physiological situations by considering the magnitude of fluid forces that are exerted on flowing red blood cells. As has been discussed in earlier work reported from our laboratory [32], our parallel-plate flow-cell conditions are essentially comparable to those that are observed in human capillaries/pre-capillaries. In this
earlier work the same trap as is used in the present studies was utilized to probe hydrodynamic fluid forces of magnitude comparable to those that act on red cells in the human microvasculature. In the context of work that is presented here, we have computed the value of the fluid force, \( F \), that is experienced by each flowing red cell as \( F = 6\pi \eta av \), where \( \eta \) denotes the viscosity of the medium, \( a \) is the radius of the red cell, and \( v \) is the flow velocity that is directly measured from our real-time movies. For simplicity of analysis, we assume that the RBCs are spherical particles. To appreciate the magnitude of flow-generated forces experienced by the RBCs consider the following: for human veins typical flow velocities range from \(5 - 20 \times 10^7 \text{ } \mu\text{m s}^{-1}\) and the corresponding fluid force experienced by a red cell varies from 20 to 85 nN (taking the value of viscosity to be 3.2 cPoise). Similarly, in the case of human arteries, typical flow velocities lie in the range \(5 - 40 \times 10^7 \text{ } \mu\text{m s}^{-1}\); the mean fluid force lies in the range 20–170 nN. In the arteries, however, the flow is in pulses and the cells are thus subjected to a fluctuating range of fluid forces. In the capillaries, with an average flow velocity of \(100-500 \text{ } \mu\text{m s}^{-1}\), typical force values are 40–210 pN. We note that in the human vasculature typical capillary diameters range from 2–20 \(\mu\text{m}\) while pre-capillaries are generally larger, typically double in size. The experiments that we report here are in the nature of a ‘proof of concept’ as far as applications in the biomedical sciences are concerned; introduction of tightly focused laser light into capillaries or pre-capillaries by means of appropriately sized optical fibres equipped with micro-lenses remains a technical challenge that might need to be addressed by means of a combination of conventional optical fibre coupled to a sub-micron diameter tapered fibre [33] that can be inserted into capillaries and pre-capillaries. The use of a tapered fibre will also obviate the need for a micro-lens; the tapered fibre mimics a large numerical aperture situation wherein an additional lens is no longer necessary for focusing. The introduction of present-day optical fibres into larger arteries is certainly feasible and is likely to be effective. Unfortunately, limitations of fast imaging technology has precluded measurements at fluid flow rates that are appropriate to arterial blood flows, although there appears to be no obvious reason why the results obtained in the present measurements cannot be extrapolated to higher flow velocities.

4. Conclusion

In summary, we have modified an optical tweezers set-up to generate, in a controlled fashion, microbubbles in flowing, biologically relevant fluids and, under static conditions, in human whole blood containing CNTs. Such bubbles are trapped by temperature driven effects at the tweezers’ focal point. Proximate CNTs too are driven towards the focal spot, where on encountering the bubble, they adhere to it. Such CNT-loaded microbubbles can be transported both along and against the flow of the surrounding fluid, and can also be exploded to cause fragmentation of the bundles. Thus, microbubbles may potentially be of use in scavenging, transporting and dispersal of potentially toxic CNTs in biologically relevant environments. A key feature of our experiments has been the use of very low power (5–10 mW), infrared, continuous wave laser light. The optical energy that is deposited into the irradiated samples is much less in our experiments than in the pioneering work of Zharov et al involving nanosecond laser pulses [21–23]. We believe that this is an important facet of our work, especially in the context of possible applications in biomedical environments.

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emission from carbon nanotubes spatially constrained on a micro-bubble \( \text{Opt. Express 17 9614–9} \)


