

RESEARCH ARTICLE

# Production and characterization of polymer microspheres containing trace explosives using precision particle fabrication technology

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## Abstract

Well characterized test materials are essential for validating the performance of current trace explosive detection systems. These test materials must replicate trace explosive contamination in the form of small particles with characteristic diameters in the micrometer range. In this work, Precision Particle Fabrication was used to fabricate monodisperse polymer microspheres that contain high explosives. Three high explosives were successfully incorporated into the microspheres. Ion mobility spectrometry confirmed that the encapsulation efficiency was typically greater than 50%, with some suspected loss to the aqueous phase during production. This study demonstrates that, with this technique, polymer microspheres containing explosives can be produced with sufficient encapsulation, along with tightly controlled particle size distributions at high production rates. These microspheres have proven to be a valuable test material for trace explosive detectors because of their highly precise size, shape and explosive composition.

**Key words:** *Explosives; microencapsulation; microspheres; trace detection*

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## Introduction

The detection of trace explosives has become a significant area of research and development within the scientific community, owing its status to the ever-increasing threat of terrorist activities around the world. The National Institute of Standards and Technology (NIST) is involved in a chemical metrology programme with the NIST Office of Law Enforcement Standards and the Department of Homeland Security Transportation Security Laboratory to improve trace explosive detection technology. Current efforts at NIST focus on the development of new measurement tools and techniques that allow researchers to study each aspect of trace detection, along with providing standard test materials to validate the performance of explosive trace detectors (ETDs).

Detecting trace levels of explosives relies on the successful collection of micrometre-sized explosive particles which have contaminated a person or object that has been

in contact with a larger bulk explosive device. Two approaches are used for collecting these particles: portal-based instruments and swipe-based instruments. In portal-based detectors, a human subject enters a semi-enclosed portal and is interrogated by a series of air-jets, air-blades and/or fans that seek to liberate explosive particles from the body, then aerodynamically transport them to a collection device (usually a mesh filter). In swipe-based systems, a security screener uses a collection trap to swipe the surfaces of purses, laptops and other articles. This swipe or mesh filter is then heated, vapourizing any explosive particles that have been collected. Explosive vapours are then transported to the instrument detector, usually an ion mobility spectrometer (IMS).

Well characterized test materials are essential for validating the performance of current trace explosive detection systems. These test materials must replicate trace explosive contamination in the form of small particles with characteristic diameters in the micrometre

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range (Verkouteren 2007). Previously, Fletcher et al. (2008) successfully incorporated high explosives into polymer microspheres using a piezo-electric inkjet printing method. Here, Precision Particle Fabrication (Berkland et al. 2001) is evaluated for producing monodisperse polymer microspheres containing high explosives. Particle size, chemical composition and detector response are particularly important. Control of sphere size has several key implications for imitating real-world trace explosive contamination. For example, the characteristic particle size of trinitrotoluene (TNT) may be very different from that of Composition-4 (C4). By controlling the diameter, one can tailor these standard test particles to mimic the true threat that exists from real-world trace explosive contamination.

Microsphere production and encapsulation have been well studied by the pharmaceutical industry (Langer 1990, Wang and Wu 1997, Wang et al. 2000, Wu 2004). The benefits of polymer encapsulation for more volatile analytes include increased stability, safety and lifetime. There are numerous techniques for producing microspheres, which include spray-drying, phase separation, electrospraying and suspension and emulsion polymerization techniques (Vanzo 1972, Kamiyama et al. 1993, Bugarski 1994, Amsden et al. 1997, Lacasse et al. 1997, O'Donnell and McGinity 1997, Wang et al. 2004, Hong et al. 2005). In these techniques, microsphere formation is a thermodynamically driven process and is governed by many parameters, many of which are difficult to control. Most of these methods do not control the uniformity and size distribution of the resultant microspheres, which is why Precision Particle Fabrication is explored here.

## Materials and methods

### Materials

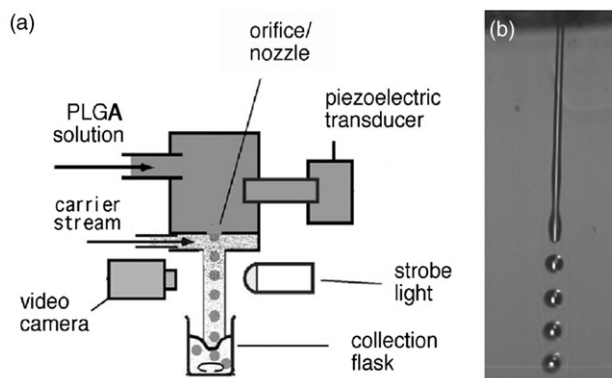
The copolymer poly(DL-lactide/glycolide) acid (PLGA) (Sigma Aldrich, St. Louis, MO) was used to encapsulate the analyte. The biodegradable and biocompatible nature and safety profile make PLGA suitable as a drug delivery platform for use in humans (Okada and Toguchi 1995, Ignatius and Claes 1996, Jain et al. 1998, Graham et al. 1999, Birnbaum and Brannon-Peppas 2003, Pack et al. 2005). PLGA degrades *in vivo* to produce biocompatible, toxicologically safe by-products (Anderson and Shive 1997) (such as lactic acid) (Fu and Pack 2000) which are further eliminated by the normal metabolic pathways of the human body (Lenz 1993). This study uses an 85:15 ratio of lactide-to-glycolide. Lactide-rich PLGA copolymers are less hydrophilic, absorb less water and subsequently degrade more slowly (Jain 2000). Three high explosive substances have been used for these

experiments: cyclotrimethylenetrinitramine (RDX), trinitrotoluene (TNT) and pentaerythritol tetranitrate (PETN).

### Precision particle fabrication

Microspheres were prepared by an oil/water emulsion process using a Precision Particle Fabrication (PPF) nozzle to deliver precisely controlled microdrops of the polymer/analyte solution into a beaker of water. In this approach, the polymer is dissolved in dichloromethane (DCM) or ethyl acetate (EtAc) with a known amount of the explosive added to the solution. A small amount of fluorescent dye is incorporated in the polymer solution to facilitate automated counting with fluorescence microscopy.

PPF uses a coaxial nozzle to create precisely controlled liquid droplets (Berkland et al. 2001). A schematic diagram of the PPF nozzle is illustrated in Figure 1. The PLGA/analyte solution is forced via a syringe pump (New Era Pump Systems, Wantagh, NY) through a 22-gauge hypodermic needle at flow rates from  $1\text{--}10\text{ mL h}^{-1}$ . An annular immiscible stream of water containing a mass concentration 0.5% polyvinyl alcohol (PVA) surfactant flows around the emerging PLGA/solvent stream at flow rates from  $60\text{--}90\text{ mL h}^{-1}$  by a second syringe pump. Both streams are forced through an orifice  $200\text{ }\mu\text{m}$  in diameter at the tip of a glass capillary tube. The entire nozzle assembly is attached to the tip of a sonic probe controlled by a frequency generator. The applied frequency of the transducer generates periodic instabilities in the jet which breaks the stream of PLGA solution into uniform liquid droplets. Liquid jets tend to break up naturally into non-uniform droplets. However, by applying periodic acoustic excitation, one can control the process and cause the



**Figure 1.** (a) Schematic diagram of the PPF nozzle (adapted from Berkland et al. 2001). (b) Stroboscopic image of the nozzle producing uniform liquid droplets. The droplets undergo a solvent extraction process which cures them into hardened spheres with high explosives incorporated inside the polymer matrix.

droplets to form at a uniform diameter. Droplet size can be controlled such that final microsphere diameters range from 5  $\mu\text{m}$  to  $\sim 90 \mu\text{m}$ , depending on the operating parameters.

The jetting process takes place under water (Radulescu et al. 2003, 2005, Bohmer et al. 2006) where the microspheres are collected and cured in a 2 L beaker containing a known amount of PVA. The water and polymer phases are immiscible, leading to the formation of an emulsion. The surfactant is used for emulsion stabilization and is a widely used additive for polymer spheres prepared by emulsification methods (Shakesheff et al. 1997).

Methods to control microsphere diameter include (i) concentration of polymer used in the solution formulation, (ii) the ratio of water-to-PLGA flow rates and (iii) the frequency of the sonic probe. Generally, as the PLGA flow rate is reduced, the droplets become smaller. As the water flow rate is reduced, the length of the laminar jet emitted from the nozzle decreases. As the frequency is increased, the droplet diameter becomes smaller.

During a microsphere production run, the nozzle and droplets must be visualized to tune the droplet diameter to the desired size and ensure the jetting process is stable. A 2 L visualization beaker with a flat window was designed for tuning and visualizing the nozzle for a specific droplet size. The flat window protrusion allows the camera to focus on the droplets. Without the visualization beaker, the curved walls of a standard beaker make it difficult to visualize individual droplets.

The experimental procedure for producing a batch of microspheres is as follows. First, the flow rate ratio and frequency required for a desired microsphere diameter are set. These settings are established by tuning each variable while the nozzle is submerged in the visualization beaker resting on a mobile platform. Once the jetting process is stable and the droplets are forming at the intended size, the visualization beaker is lifted off of the mobile platform, the platform is rolled off to the side and the visualization beaker is removed from the set-up. A new 2 L beaker with PVA water replaces the visualization beaker and the platform is rolled back underneath the new beaker, fully-submerging the nozzle tip. The PPF nozzle will continue to operate correctly outside of a submerged water environment, so this quick switch of beakers is not problematic. A magnetic stir bar and stir plate (Fisher Scientific, Pittsburgh, PA) are used to stir the water and help prevent the spheres from settling before being fully-cured. The jetting operation continues uninterrupted for as long as necessary to produce the required number of microspheres. Once the jetting is finished, the droplets are left to stir for several hours until they are fully cured and hardened. A typical run lasts anywhere from 30 min to 3 h, depending on the volume of polymer solution used in the experiment. Since each oscillation of the sonic probe produces one

liquid droplet, a 2-h production run operating at 8 kHz generates a final microsphere batch containing  $\sim 58$  million microspheres.

Once the microspheres have been cured for 2 h, the beaker is separated from the magnetic stir-plate and the magnetic stir-bar is removed from the bottom of the beaker. The microsphere/water suspension is set aside, usually overnight, to allow the spheres to settle to the bottom of the beaker. When the spheres have collected on the bottom, the water (supernatant) is carefully removed, leaving  $\sim 50$  mL of water and microspheres at the bottom of the beaker. This concentrated sphere suspension is then pipetted into a centrifuge vial and centrifuged at 4000 rpm for 5 min. This fully separates the microspheres from the liquid phase. After the 5-min centrifuge, the supernatant is removed from the vial and replaced with an equal amount of clean, filtered water. This cleaning process is repeated three times to remove any excess PVA from the surfaces of the microspheres (Bangs Laboratories 1999). Finally, purified microspheres are either placed in a 20 mL vial with water or lyophilized (Model BT2K, SP Industries, Warminster, PA) for 24 h or 48 h. Dried microspheres are stored under vacuum in the presence of desiccant.

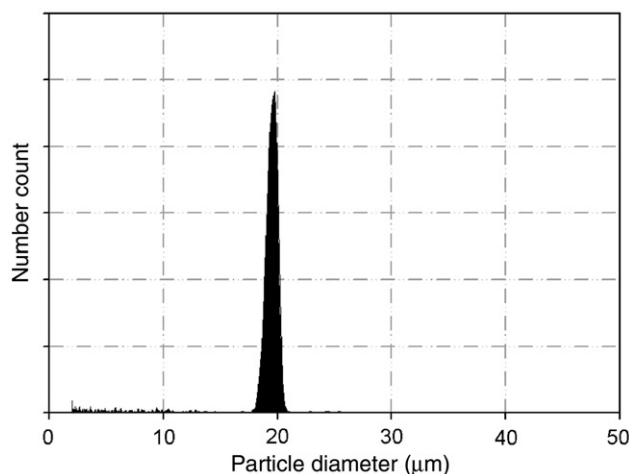
### *Light and electron microscopy*

Droplet formation is visualized by a micro-stroboscopic technique where a strobe light (Advanced Illumination, Rochester, VT) flashes at a frequency tuned to that of the sonic probe. The image viewed by a digital camera fixed with a microscope objective 'freezes' the process, allowing visualization of still droplets (Figure 1(b)).

Surface morphology is characterized by environmental scanning electron microscopy (FEI Quanta 200 FEG-ESEM, Hillsboro, OR). Hardened microspheres were filtered onto 0.4  $\mu\text{m}$ -pore Whatman filters, then dry-transferred onto silicon wafers attached to imaging stubs. All imaging was performed under high-vacuum at an accelerating voltage of 1 keV. Additional microsphere imaging was performed with white-light and fluorescent microscopies.

### *Particle size distribution*

Cured PLGA microspheres were characterized with a Beckman Coulter Multisizer 3 (Beckman Coulter Inc., Fullerton, CA) where a 100  $\mu\text{m}$  sampling orifice measures particle diameter in the range of 0.2–60  $\mu\text{m}$ . An aliquot of cured microspheres in aqueous suspension is added to 50 mL of isotonic solution for analysis. Sampling time was set to 2 min.



**Figure 2.** Particle size distribution of microspheres produced by PPF.

### *Ion mobility response*

The response of explosive-containing microspheres was evaluated in a commercially available IMS trace explosives detector. Microspheres were deposited from aqueous suspension onto a glass slide with a dropper bottle. Then the microspheres were counted using fluorescence microscopy with automated stage control and counting software (Verkouteren et al. 2008). Woven-fibre swipes used for this particular ETD were used to collect the microspheres from the glass slide. The swipe was then introduced into the ETD for chemical analysis.

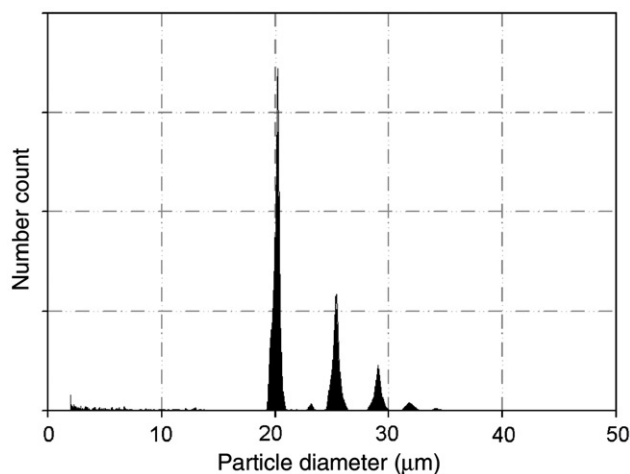
Standard solutions of explosives in acetonitrile (Restek, Bellefonte, PA) were used to create a calibration curve for comparison to the response of the microspheres. Aliquots of a given concentration were pipetted onto swipes, allowed to dry and then introduced to the IMS. A total of five replicates were performed at each mass level.

## **Results**

### *Monodispersity*

The PPF nozzle is capable of producing monodisperse batches of microspheres. A typical particle size distribution of microspheres is shown in Figure 2, where the mean diameter of the spheres is 19.6 μm, the standard deviation (SD) is 0.5 μm and the coefficient of variance (CV) is 2.4%.

One key variable that determines the successful production of monodisperse spheres is the amount of PVA added into the annular water and beaker water. PVA acts as an emulsion stabilizer and prevents two liquid droplets from coalescing into a larger droplet while stirring in the beaker of water during production. Without adequate



**Figure 3.** Particle size distribution showing an example of coalescing microspheres generated when an insufficient concentration of PVA is used.

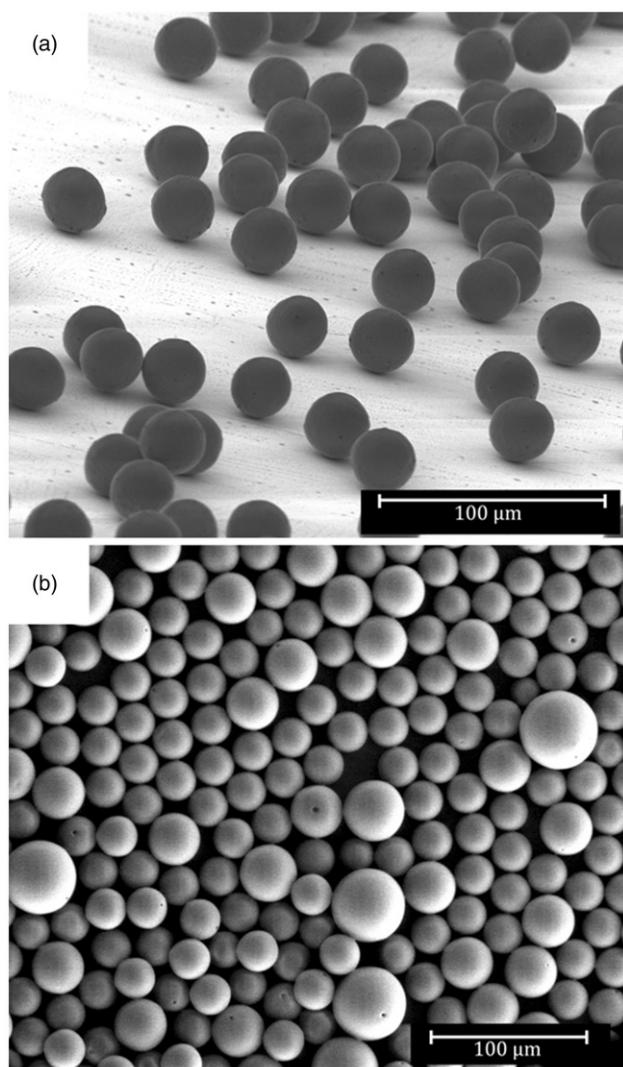
PVA present in the water, particle size distributions like the one shown in Figure 3 are created. In Figure 3, the main peak at 20.5 μm represents the majority of microspheres in the batch. However, the second peak at 25.5 μm corresponds to droplets that have coalesced. Additional peaks scale as multiples of the cube root of the number of droplets coalescing ( $n$ ) multiplied by the initial diameter ( $n^{1/3} \times \text{diameter}$ ; for  $n = 1, 2, 3, \dots$ ). Other processes can cause this effect as well, such as unstable jetting, satellite production or deficient mixing in the 2 L beaker during production.

Levels ranging from mass concentration 0.1–0.5% of PVA were tested under a variety of conditions. Both the annular water and the beaker water contained equivalent PVA concentrations. It was determined, for this system, that a mass concentration 0.5% PVA is the lower limit of PVA needed to effectively eliminate coalescence. It is still unclear if higher concentrations of PVA, for example mass concentration 3% PVA, will adversely influence the resulting microspheres. However, since the droplets no longer coalesce above mass concentration 0.5% PVA, it is unnecessary to go above this concentration. Scanning electron micrographs of the batches discussed in Figures 2 and 3 are given in Figure 4.

### *Polymer concentration*

The concentration of polymer in the solvent solution can affect the final microsphere diameter. In the example shown in Figure 5, various concentrations of polymer/solvent were jetted to form microspheres. Each batch was created with the same operating parameters, i.e.

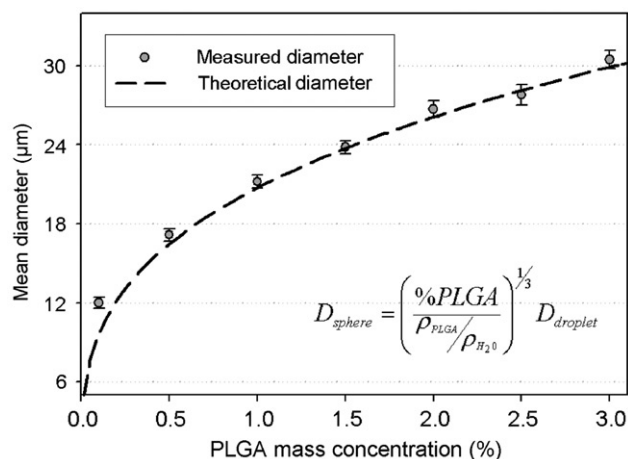




**Figure 4.** Scanning electron micrographs of PLGA microspheres. (a) Monodisperse microspheres produced by using a sufficient PVA concentration in the aqueous phase. (b) Coalesced microspheres produced without sufficient PVA concentration.

frequency and ratio of polymer/water flow rate, which produces equivalent-diameter liquid droplets into the water. The concentration of polymer was varied from mass concentration 0.1% (1 mg PLGA/mL DCM) to 3% (30 mg PLGA/mL DCM).

Results shown in Figure 5 demonstrate that an increase in the concentration of polymer used in the jetted solution will increase the final cured microsphere diameter, even when the primary liquid droplets are equivalent in diameter. For example, if a mass concentration 3% PLGA is being jetting into liquid droplets of 105 μm in diameter, then each droplet contains 18.2 ng of PLGA. By comparison, a mass concentration 0.1% PLGA concentration jetting 105 μm droplets contains 0.6 ng PLGA per droplet.



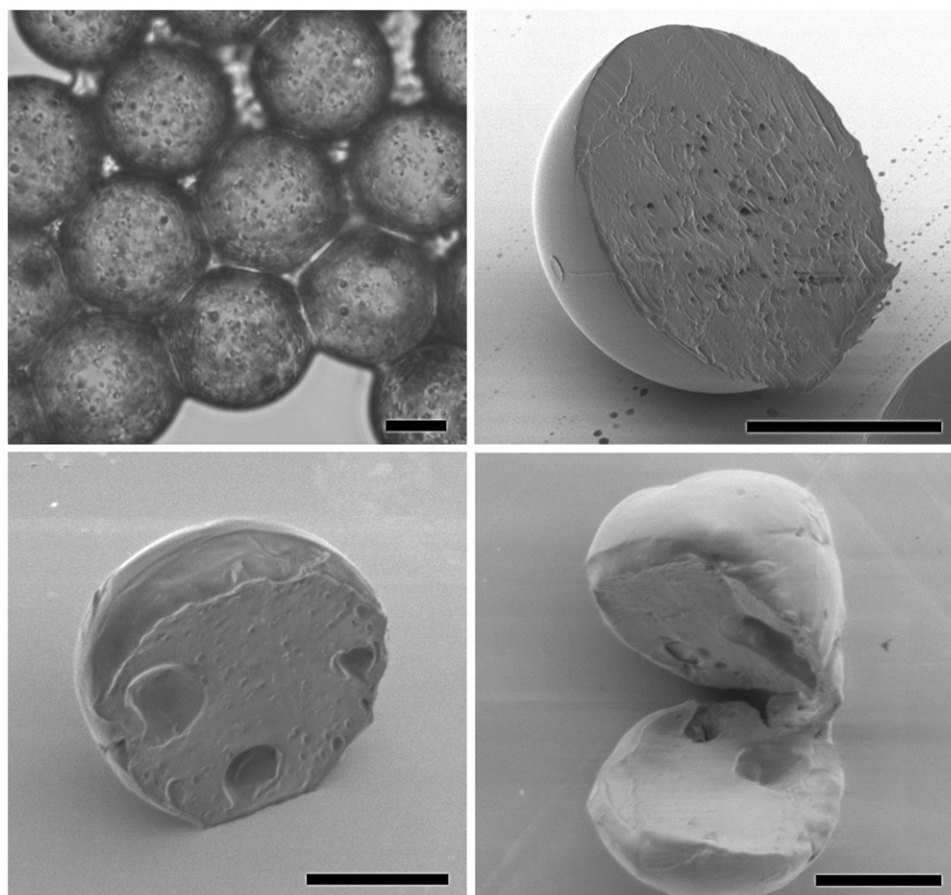
**Figure 5.** Comparison of seven cured PLGA microsphere batches made from different initial polymer concentrations but produced with the same jetting parameters. In each case, the initial liquid droplet diameters were equivalent but the final cured diameters increase with polymer concentration. Uncertainties are the standard deviation of the size distribution.

Once all solvent has diffused from the droplets, the mass concentration 3% PLGA droplet now becomes a 30 μm hardened microsphere while the mass concentration 0.1% PLGA droplet becomes only 12 μm in diameter because of the differences of PLGA mass in the initial liquid droplets.

### Microsphere density

The calculation of mass of explosive per sphere is based on the sphere density. This density value assumes the sphere to be that of the homogeneous PLGA; however optical and scanning electron micrographs (SEM) of cross-sectioned PLGA microspheres reveal that this assumption is not correct. Figure 6 shows microscope images of spheres with porous internal structures along with voids and inclusions.

A concern was that there may be a distribution of densities due to the inhomogeneous void structures inside each microsphere. To assess the density differences across a large population of spheres, a linear density gradient column (Oster and Yamamoto 1962) was used. To make the density gradient column, 100 g of calcium nitrate was dissolved in 70 mL H<sub>2</sub>O to make a solution with a density much greater than pure water. The density was measured to be greater than 1.4 g cm<sup>-3</sup>. This dense aqueous solution is mixed into a mixing chamber of a water/calcium nitrate solution with a density of 1.1 g cm<sup>-3</sup> at a constant flow rate. At the same time, the mixing chamber is being drained slowly into the bottom of a vertical glass column with flat walls. The mixing chamber solution



**Figure 6.** Optical and SEM images of cross-sectioned PLGA microspheres cut by a razor blade. The scale bar in each image is 10  $\mu\text{m}$ . These images illustrate that the interior microsphere structure is not entirely homogeneous. Pores are present inside the microsphere, suggesting that the microsphere density is less than the bulk density of PLGA.

increases in density at a constant rate as the dense solution mixes with the pure water. In doing so, the vertical glass column fills with continuously-increasing density fluid. A detailed description of how to properly construct linear density gradient columns can be found in the ASTM Standard D-1505-03 (2003).

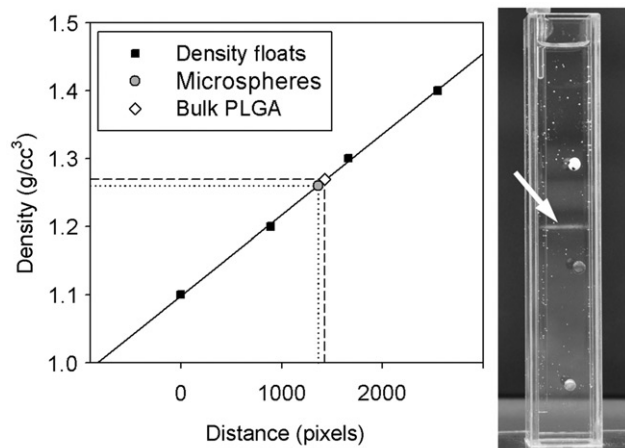
Once the density gradient is created, calibrated glass floats of precise density (American Density Materials Inc., Staunton, VA) are introduced into the density column and sink to a point where their density matches that of the solution in the column. Then, an aliquot of explosive-containing microspheres in aqueous solution is placed in the column and allowed to sink to their appropriate density. A high-resolution digital image is taken of the settled glass floats and microspheres and image processing is used to interpolate the final microsphere density.

With this technique, the density of bulk PLGA was measured to  $1.27 \text{ g cm}^{-3}$ ; however, the images in Figure 6 suggest that the density of PLGA microspheres will be less due to the porous nature of the polymer micro-environment.

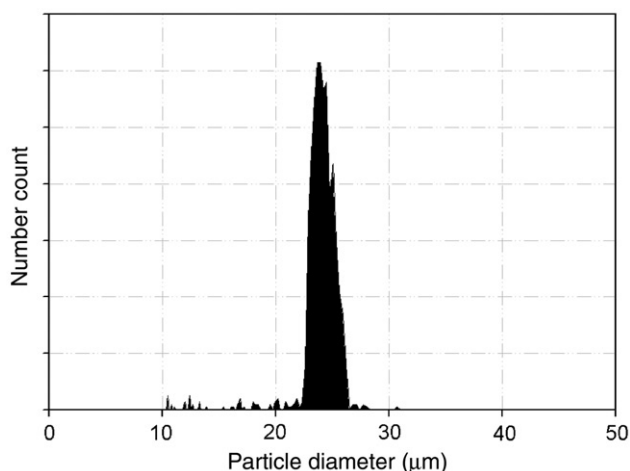
Each batch of microspheres, PETN, RDX and TNT, were examined in a density gradient column and found to be  $1.26 \pm 0.005 \text{ g cm}^{-3}$  for all three explosives. The uncertainty was determined by measuring the thickness of the line to which the microspheres settled. An image of the density gradient column with mass fraction 0.5% PETN microspheres, along with a plot of the linearity of the calibrated glass floats, is found in Figure 7. In the image of the density gradient column, the top surface of liquid has a density of  $1.1 \text{ g cm}^{-3}$ . The calibrated floats are 3 mm in diameter and have densities of 1.2, 1.3 and  $1.4 \text{ g cm}^{-3}$  and are accurate to  $0.0002 \text{ g cm}^{-3}$ .

#### *IMS detection response*

The formulation for a batch of 0.5% mass fraction PETN/PLGA microspheres was prepared by adding  $187.5 \mu\text{L}$  of  $4 \text{ mg mL}^{-1}$  solution of PETN in DCM into 5 mL of a  $30 \text{ mg mL}^{-1}$  solution of PLGA in DCM. Droplets of uniform size were created in water by forcing the



**Figure 7.** Density gradient column linearity expressed as density as a function of distance measured in pixels. Error bars are too small to be seen on this scale. The PETN microspheres can be seen as a faint line near the centre of the vertical column highlighted with an arrow.

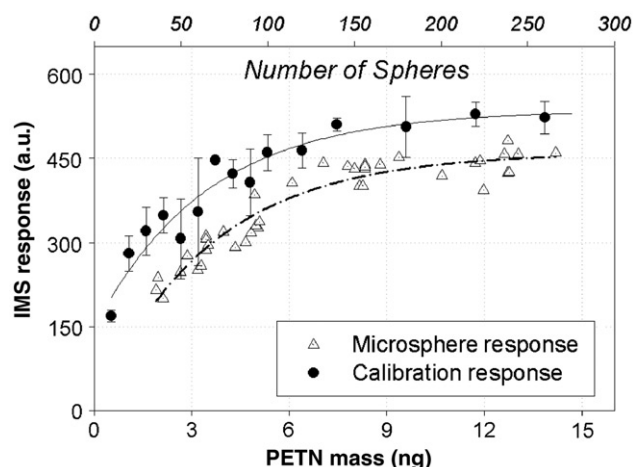


**Figure 8.** Particle size distribution of the 0.5% mass fraction PETN/PLGA microsphere batch used for microsphere response experiments.

explosive/polymer solution through the nozzle at  $4 \text{ mL h}^{-1}$  and the annular water stream at  $66 \text{ mL h}^{-1}$ , while applying a 4 kHz sinusoidal waveform to the sonic probe at an amplitude of 2 V. Hardened microspheres cured to a final diameter of  $24.2 \mu\text{m}$ , as illustrated in Figure 8.

With a mean diameter of  $24.2 \mu\text{m}$ , a theoretical mass calculation, assuming 100% encapsulation efficiency and a particle density of  $1.26 \text{ g cm}^{-3}$ , yields  $46.9 \text{ pg}$  PETN per microsphere. With the theoretical mass per particle, along with the number of microspheres introduced to the IMS, one can calculate the total mass analysed.

A total of 40 swipes containing varying levels of PETN-containing microspheres were analysed by the IMS. A calibration response curve was produced by solution deposition with the same IMS to study how well the



**Figure 9.** Detector response of PETN-containing microspheres in a commercially available ETD. Calibration response was determined by standard solution deposition. Uncertainties in the calibration response are the standard deviation of five replicates.

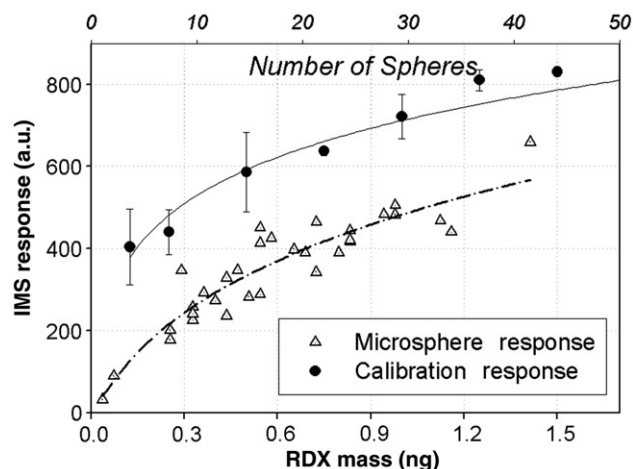
microspheres compare to standard reference solutions of explosives. Figure 9 shows the response curve of PETN-containing microspheres as a function of number of microspheres and mass of PETN. Note that IMS response curves typically demonstrate a linear rise-to-max and eventually reach a saturation point where the addition of more explosive material no longer increases the magnitude of response.

Both the calibration response and the microsphere response have trends that match well. This agreement in trends proves that explosive-containing microspheres have utility as a quantitative test material for trace explosive detectors. For simple screening applications where there is a pass/fail test, the spheres should perform as excellent test materials.

As illustrated in Figure 9, the PETN-containing microspheres do not respond at their intended level, suggesting that the encapsulation efficiency is less than 100%. The authors speculate that there are two reasons for this: (1) there is some diffusion of explosives from the liquid droplet into the aqueous phase during the microsphere curing process; and (2) the microspheres are not releasing all of the explosives during the instrument desorption cycle. As described in the Precision particle fabrication section, the liquid droplets that are jetting into water undergo a solvent extraction process where the solvent diffuses from the droplet into the aqueous phase. During this process, small amounts of explosives are also diffusing into the aqueous phase resulting in decreased encapsulation efficiency of explosives in the microsphere.

When a swipe is introduced into the ETD, it is heated to facilitate rapid vapourization of explosive particles collected. When the explosive-containing microspheres are heated, the polymer releases the majority of explosives,





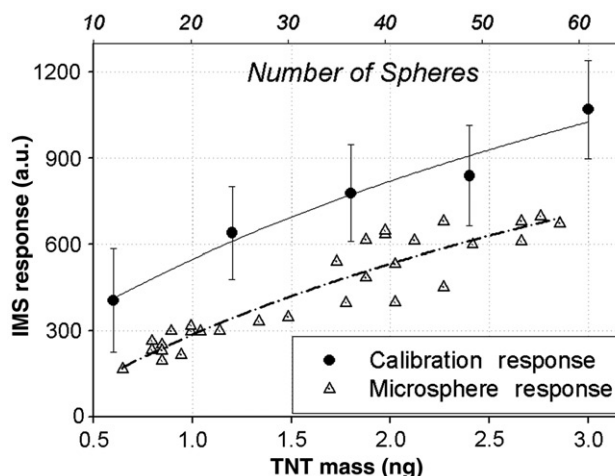
**Figure 10.** Detector response of RDX-containing microspheres. Calibration response was determined by standard solution deposition. Uncertainties in the calibration response are the standard deviation of five replicates.

but some analyte remains trapped in the melted polymer. This has been qualitatively confirmed by detecting additional trace explosives on the same swipe during a second heating cycle in the IMS.

Similar results are observed with the high explosives RDX and TNT. A batch of mass fraction 0.5% RDX was produced by adding 1.5 mL of 0.5 mg mL<sup>-1</sup> RDX in EtAc solution to 5 mL of 30 mg mL<sup>-1</sup> PLGA in EtAc solution. Droplets of uniform size were created in water by forcing the explosive-polymer solution through the nozzle at 3 mL h<sup>-1</sup> and the annular water stream at 25 mL h<sup>-1</sup>, while applying a 3.2 kHz sinusoidal waveform to the sonic probe at an amplitude of 2 V. Resulting microspheres had a mean diameter of 22.0 µm and a standard deviation of 0.5 µm.

Similarly, a batch of mass fraction 0.5% TNT was produced by adding 1 mL of 1 mg mL<sup>-1</sup> TNT in DCM solution to 6.63 mL of 30 mg mL<sup>-1</sup> PLGA in DCM solution. Droplets were formed in water by jetting the explosive-polymer solution at 4 mL h<sup>-1</sup> and the annular water stream at 45 mL h<sup>-1</sup>, while applying a 4 kHz sinusoidal waveform to the sonic probe at an amplitude of 2 V. The cured microspheres had a mean diameter of 24.0 µm and a standard deviation of 0.7 µm.

The procedure for analysing IMS response of RDX and TNT microspheres is identical to that of the PETN microspheres. Results for RDX and TNT are given in Figures 10 and 11. Each batch of microspheres exhibits a response slightly lower than expected. With PETN, the microspheres exhibit a 15% decrease in response on average. RDX has a 25% reduction in response and TNT shows a decrease of almost 50%. Note that the scatter in the standard



**Figure 11.** Detector response of TNT-containing microspheres. Calibration response was determined by standard solution deposition. Uncertainties in the calibration response are the standard deviation of five replicates.

calibration response is similar to that of the encapsulated microspheres, suggesting similar precision.

## Summary and future directions

A new method for making explosive particle test materials has been developed. One is producing monodisperse polymer microspheres encapsulating explosives via a vibrating coaxial Precision Particle Fabrication nozzle. These spheres are valuable because they provide characterized particulate materials of known shape, size and composition. Polymer microspheres are an attractive delivery platform for the testing of trace explosive detection instruments for several reasons: real-world explosive contamination typically comes in the form of micrometre sized particles, both particle size and composition can be tailored, microsphere morphology is useful for aerodynamic studies and the polymer matrix may extend the lifetime of more volatile analytes. The biodegradable copolymer PLGA is used to encapsulate the analyte because of its biocompatibility and safety profile which have made it suitable in pharmaceutical applications. With precise control over operating parameters, Precision Particle Fabrication produces monodisperse microspheres with high particle yields, producing tens of millions of microspheres in an hour.

This study has successfully incorporated a number of explosive compounds into microspheres, including the high explosives RDX, PETN, TNT. Ion mobility spectrometry has revealed that the encapsulation efficiency of explosive in polymer is not 100% for each explosive. Future work



will quantify the true chemical composition of the microspheres by UV-Vis spectrophotometry, mass spectrometry and solid-phase microextraction and examine trends between encapsulation efficiency and explosive mass fraction. However, IMS instruments implemented in the field and used by security screeners are binary pass/fail systems, thus knowing exactly the concentration of explosives per sphere is not critical. The authors also plan to investigate the spatial distribution of analyte within the sphere with secondary ion mass spectrometry, focusing on the presence of any mass gradients within the interior of the polymer matrix. The authors also plan to make more elaborate explosive microspheres which would contain more than one explosive compound per sphere. Examples of some combinations are Composition B (RDX + TNT), Composition C4 (RDX + poly(isobutylene) binder), PTX-2 (RDX + TNT + PETN) and Semtex (RDX + PETN + poly(styrene-butadiene) binder) (Yinon 1999).

The explosive-encapsulated microspheres are useful as semi-quantitative test particles, but one is striving to carefully quantify the true level of explosive in each batch. The actual microsphere response in ETD instruments is critical. For these microspheres to be functional test particles for ETD machines, the PLGA polymer must not adversely interact with the chemistry of the instruments and produce erroneous responses. This study has shown that PLGA does act as a barrier and restrain some explosive from being desorbed upon the first heating cycle; however, no evidence was found that PLGA is an interference with the IMS chemistry in current instruments. Future work will explore the performance of the microspheres in a wide variety of ETD instruments.

Finally, a functional vehicle must be developed for delivering a known quantity of microspheres to a detection instrument. Two possible systems have been proposed: Dropper bottle deposition for dry-transfer swiping in benchtop ETD instruments and metered dose inhalers for aerosolizing spheres into portals. Both methods are being investigated.

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**Declaration of Interest:** The authors declare that there are no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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