Integrated chemical/biochemical sample collection, pre-concentration, and analysis on a digital microfluidic lab-on-a-chip platform

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ABSTRACT

An ideal on-site chemical/biochemical analysis system must be inexpensive, sensitive, fully automated and integrated, reliable, and compatible with a broad range of samples. The advent of digital microfluidic lab-on-a-chip (LoC) technology offers such a detection system due to the advantages in portability, reduction of the volumes of the sample and reagents, faster analysis times, increased automation, low power consumption, compatibility with mass manufacturing, and high throughput. We describe progress towards integrating sample collection onto a digital microfluidic LoC that is a component of a cascade impactor device. The sample collection is performed by impacting airborne particles directly onto the surface of the chip. After the collection phase, the surface of the chip is washed with a micro-droplet of solvent. The droplet will be digitally directed across the impaction surface, dissolving sample constituents. Because of the very small droplet volume used for extraction of the sample from a wide collection area, the resulting solution is relatively concentrated and the analytes can be detected after a very short sampling time (1 min) due to such pre-concentration. After the washing phase, the droplet is mixed with specific reagents that produce colored reaction products. The concentration of the analyte is quantitatively determined by measuring absorption at target wavelengths using a simple light emitting diode and photodiode setup. Specific applications include automatic measurements of major inorganic ions in aerosols, such as sulfate, nitrate and ammonium, with a time resolution of 1 min and a detection limit of 30 ng/m^3. We have already demonstrated the detection and quantification of nitroaromatic explosives without integrating the sample collection. Other applications being developed include airborne bioagent detection.

Keywords: lab-on-a-chip, digital microfluidics, sample collection, detection, analysis

1. INTRODUCTION

Much of the reported work on lab-on-a-chip (LoC) microfluidic devices has focused on miniaturization of analytical methods and protocols for the purpose of improving performance and throughput. And the benefits of miniaturization such as smaller sample requirement, reduced reagent consumption, decreased analysis time and higher levels of throughput and automation have been demonstrated. In addition, most lab-on-a-chip examples have been directed to performing chemical or biological methods on chip in which pre-prepared samples have been processed off-chip. Thus, to date little work has been reported on integrating the front-end functions, such as sample collection, concentration, and filtration, with the required analytical operations on-chip.[1]

Currently almost all microfluidic devices are based on continuous fluid flow in permanent microchannels in glass, plastic or other polymers. A review of sample pre-treatment with continuous flow microfluidic systems is presented in Ref. 1. However, continuous-flow-based microfluidic devices offer very little flexibility in terms of scalability and reconfigurability, and are usually application specific. Though pumps based on electrokinetic phenomena

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Lab-on-a-Chip: Platforms, Devices, and Applications, edited by
Linda A. Smith, Daniel Sobek, Proceedings of SPIE Vol. 5591
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.581955

(electrophoretic separation and electroosmotic pumping) dominate academic research [2, 3], there is a trend towards the use of alternative fluid actuation mechanisms, since many common samples are not directly compatible with electrokinetic phenomena. For instance, physiological fluids with high ionic strength, such as blood and urine, cannot be pumped using electroosmosis due to excessive Joule heating. [4] Among alternative active pumping mechanisms, centrifuge-based devices, which are independent of physicochemical properties of fluids, have attracted a lot of attention in the past few years. [4 5] However, the technique is better suited for use with pre-collected and pre-prepared samples.

An alternative approach towards microfluidics is to manipulate the liquid as unit-sized discrete microdroplets. Due to the architectural similarities with digital microelectronic systems, we have often referred to this approach as "digital" microfluidics. Digital microfluidic systems have several advantages over continuous-flow systems, the most important being reconfigurability and scalability of architecture [6]. Electrowetting [6] and dielectrophoresis [7] are the two most commonly used techniques for microdroplet actuation. Electrowetting is primarily a contact line phenomenon, and refers to electric field-induced interfacial tension changes between a liquid and a solid conductor. On the other hand dielectrophoresis is a bulk phenomena caused as a result of polarization induced in a dielectric liquid by a non-uniform electric field. Dielectrophoresis typically uses high frequency AC voltages (>50 KHz), which can cause significant Joule heating in aqueous samples, even at moderate ionic strengths. In contrast, there is negligible Joule heating in electrowetting, since it can use DC or low frequency AC (<100 Hz) and aqueous droplets of potassium chloride (KCl) with ionic strengths as high as 1M have been transported without any problems [6]. Electrowetting therefore appears to be a more suitable technique for a wider matrix of samples, as compared to dielectrophoresis.

The use of electrowetting for dispensing, transport, splitting, merging and mixing of aqueous droplets, has been shown previously. [6, 8-10] It has also previously been demonstrated the transport of enzyme laden droplets without loss in activity, and a complete colorimetric enzyme-kinetic glucose assay (using standard solutions) on an electrowetting chip. [11, 12] This paper extends the use of an analytical electrowetting device by integrating sample collection and pre-concentration on the same chip. The sample collection is performed by impacting airborne analyte particles directly onto the surface of the chip. After the collection phase, the surface of the chip is washed with a micro-droplet of solvent. The droplet will be digitally directed across the impaction surface, dissolving sample constituents. Because of the very small droplet volume used for extraction of the sample from a wide collection area, the resulting solution is relatively concentrated and the analytes can be detected after a very short sampling time (1 min) due to such pre-concentration. After the washing phase, the droplet is mixed with specific reagents that produce colored reaction products. The concentration of the analyte is quantitatively determined by measuring absorption at target wavelengths using a simple light emitting diode and photodiode setup. Target applications include quasi real time sampling of airborne contaminants and bioagents, and detection and quantification of nitroaromatic explosive particles.

2. METHODOLOGY

In the sections below, the basic ideas behind electrowetting devices will be presented as well as a sample collection method utilizing a scanning droplet that passes over the collection surface. Specific experimental results will be presented that demonstrate key concepts, and two applications will be discussed: 1) sampling of airborne particles in aerosol, and 2) detection of explosive particles.

2.1 Electrowetting Technology

Electrowetting-based systems have been demonstrated for manipulation of microliter and nanoliter-sized droplets in LoC protocols. [9, 11, 12] The droplets sit on a hydrophobic surface over an electrode which controls its wettability through the application of an electric field. Using this principle, discrete droplets can be transported in a highly controlled way over an array of electrodes. Such an array can be reconfigured to transport the droplets or hold the droplets as virtual reaction chambers where mixing can be formed. To view movies of electro-wetting-induced droplet motion, refer to the Duke Microfluidics Lab website at http://www.ee.duke.edu/research/microfluidics/. The digital microfluidic platform which we have used is shown below in Fig. 1. Such a platform can be used to perform simultaneous optical detection on multiple droplets.

The electrowetting actuation system consists of two parallel electrode plates – a continuous ground plate on top and an addressable electrode array as the bottom plate as shown in Figure . All the electrodes in both the top and bottom plates were fabricated on glass substrates and patterned in indium-tin-oxide (ITO). Due to its transparent nature, ITO enables easy integration of optical measurement techniques with the electrowetting system. Using standard microfabrication techniques, an array of independently addressable control electrodes were patterned on the bottom plates. It was further coated with Parylene C (800 nm) for insulation. The top glass plate was coated with a layer of ITO to form a continuous ground electrode. Both top and bottom plates were coated with a thin hydrophobic layer of Teflon AF 1600 (50 nm). A spacer separates the top and bottom plates, yielding a fixed gap. The droplet is sandwiched between the two plates, and surrounded by immiscible silicone oil. Silicone oil prevents evaporation of the droplets and also reduces the voltages required for transporting the droplets. In the experiments reported in this paper, we have used electrowetting chips with an electrode pitch (L) of 1.5 mm and gap spacing (H) of 600 μm. A custom electronic controller was built to address and switch each electrode independently.

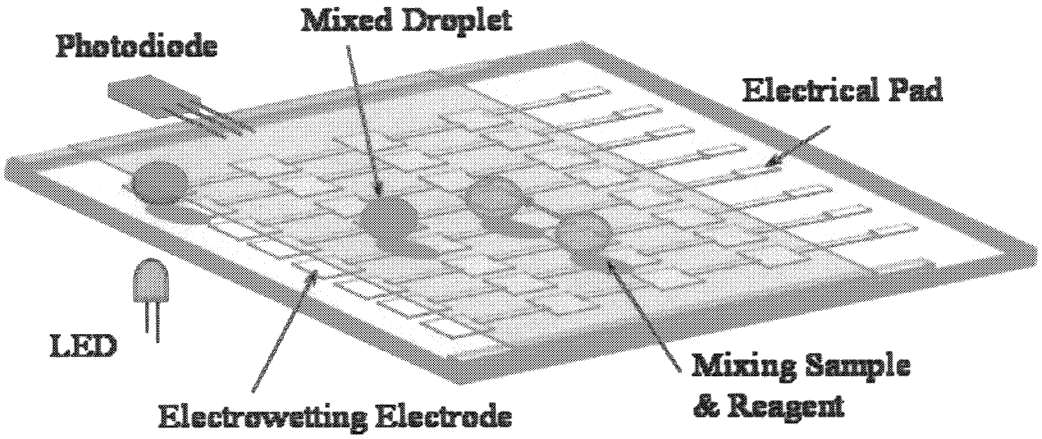

Figure 1. Schematic of the electrowetting lab-on-a-chip integrated with optical detection.

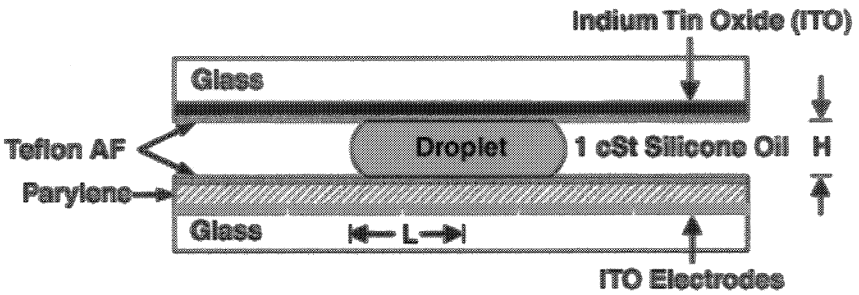

Figure 2 - Side view of the electrowetting chip showing the material layers

2.2 Sample Collection and Concentration

Sample collection is achieved by impacting a planar surface on the electrowetting chip with a stream of aerosol. After a brief collection phase, the surface of the chip is washed with a micro-droplet of ultra-pure solvent that is digitally

directed across the impaction surface, dissolving aerosol constituents. After the washing phase the droplet is mixed with specific reagents that produce colored reactions with components of interest. The concentration of the analyte can be determined by measuring absorption at specific wavelengths using on-chip light-emitting diodes and detectors. After the analysis step the sampling cycle can be repeated. Because of the very small droplet volume used for aerosol extraction, the resulting solution is relatively concentrated and the substances can be detected after a very short sampling time (1 min). The on-chip colorimetric detection using digital microfluidics has been successfully demonstrated at concentration levels expected to be found under ambient sampling conditions.

The collection surface in an impactor must be exposed to the air stream. Thus, unlike our previous work where a top plate was provided that constrained the droplet and also gave a top electrical contact, as is shown in Fig. 2, a novel coplanar design will be implemented in the proposed work. A coplanar structure allows for electrical contact to the droplet in the transport surface, and this design is shown in Fig. 3. With this design the airflow will have uninterrupted access to the collection surface on which the droplet will scan.

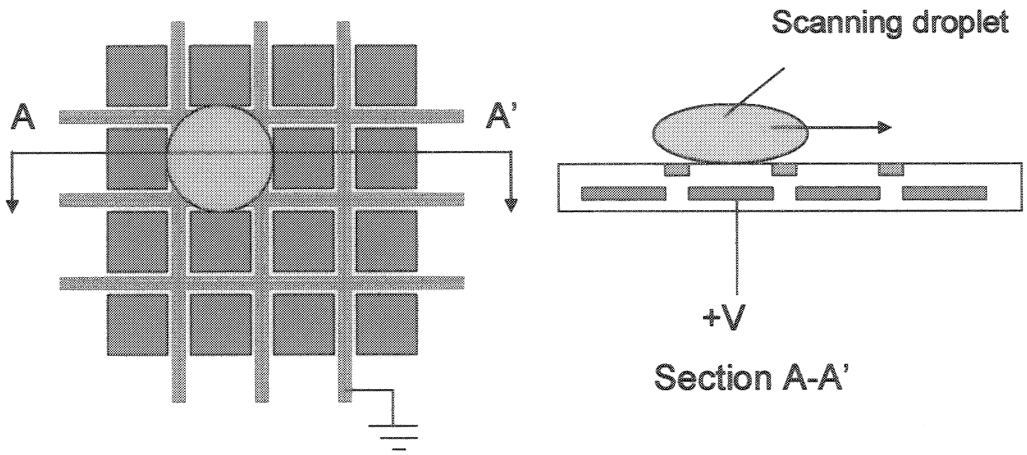

Figure 3. Coplanar actuation array for droplet scanning where electrical contact to the droplet is provided by surface electrodes, obviating the need for a top contact plate.

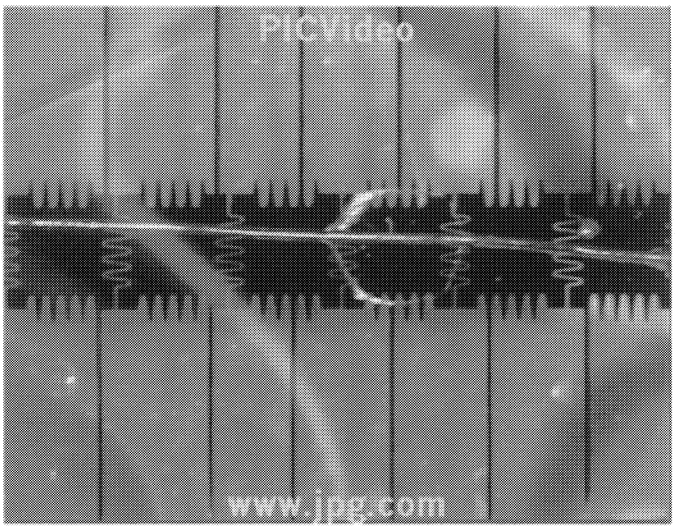

Figure 4. Micrograph of a water droplet being transported on a hydrophobic surface using the wire traction method and no top plate.

An alternative droplet actuation design that has been tested is to contact the droplet with a thin wire spaced above the hydrophobic surface. This is known as the "wire traction" transport mode. The wire can be very small in diameter as long as it passes through the droplet. As a result, a coarse grid of traction wires would overlay the grid of the buried electrodes, which would cause only a minor perturbation of the airflow at the impactor surface. A photo micrograph of a scanning droplet using the wire traction mode is shown above in Fig. 4.

The sample collection process must be interrupted (air stream blanked off) while the scanning droplet collects from the impaction surface. Otherwise, the droplet may evaporate. Droplet velocities of up to 10cm/sec have been demonstrated in our system for 1.5mm diameter droplets. At this rate, the entire impaction surface area (2.5 cm in diameter) could be scanned once in about 4 sec. Alternatively, 7 droplets could be used to scan the area in parallel in 1 sec.

In order to achieve this high scanning rate, impacted particles must be collected dynamically while the droplet is moving at high velocity. The pick-up of insoluble particles may have both positive and negative effects: it will clear up the surface, but may interfere with the photometric measurements of the analytical assay. Both of these effects are being investigated.

A demonstration of the scanning-droplet particle collection method is shown in Fig. 5. A solution containing 1μm diameter beads was diluted and deposited on the hydrophobic Teflon surface of an electrowetting chip. The beads were Molecular Probes FluoSpheres carboxylate modified microspheres. After the solvent dried, a 1μL droplet of distilled water and 2mM azide clad with a thin oil film was scanned in air across the bead-coated surface. The gap was 360 μm and the actuation voltage was 50V. The time sequence of the frames in Fig. 5 starts with the upper left frame, which shows the virgin droplet. The droplet scan in frame 1-6 is right-to-left, and in the last two frames (7, 8), the droplet is scanned left-to-right back over the cleaned surface. It can be seen that the beads are picked up by the droplet with good efficiency (frames 1-6), and that they are not re-deposited on the hydrophobic surface one they are collected (frames 7, 8).

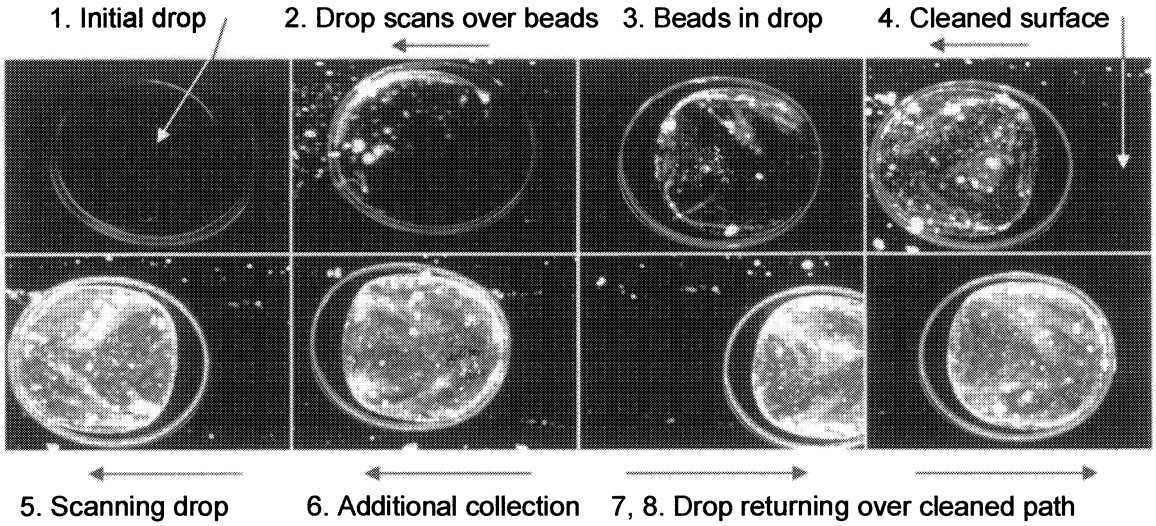

Figure 5. A demonstration of the scanning-droplet particle collection process is shown. Arrows indicate the direction of droplet scan, and the frame numbers show the time sequence. It can be seen that the deposited 1mm beads on the surface sre picked up, leaving a cleaned swath behind the droplet. No beads are re-deposited once the scan direction is reversed.

2.3 Collection Surface – LoC Interface

A 1μl water droplet will evaporate in room temperature air in about 5 min. Thus, the bulk of the LoC operations must be performed in a silicone oil medium with a top plate. The oil confined between the parallel plates of the actuator (Fig.

2) encases the droplets and prevents evaporation. However, droplet scanning and sample collection will be performed in air without a top plate, so as not to perturb impactor air flow. To prevent evaporation, the scanning droplet is clad with its own oil encasement, which surrounds the droplet and travels in air with the actuated droplet. This oil cladding is performed by transporting the droplet through the interface between the oil medium and the air.

In preliminary experiments, we have successfully transported water droplets across a silicone oil/air interface (see Fig. 6). Fluorescein diluted in water was loaded into an on-chip reservoir, whose operation has been previously described. [13] The oil/air interface exists at the edge of the first electrode outside the reservoir, as shown in Fig. 5. In the sequence of dispensing operations depicted in Fig. 6, a fluorescein droplet is dispensed through the oil/air interface. The droplets that are dispensed through an oil/air interface are clad with an oil film, which assists with their transport.

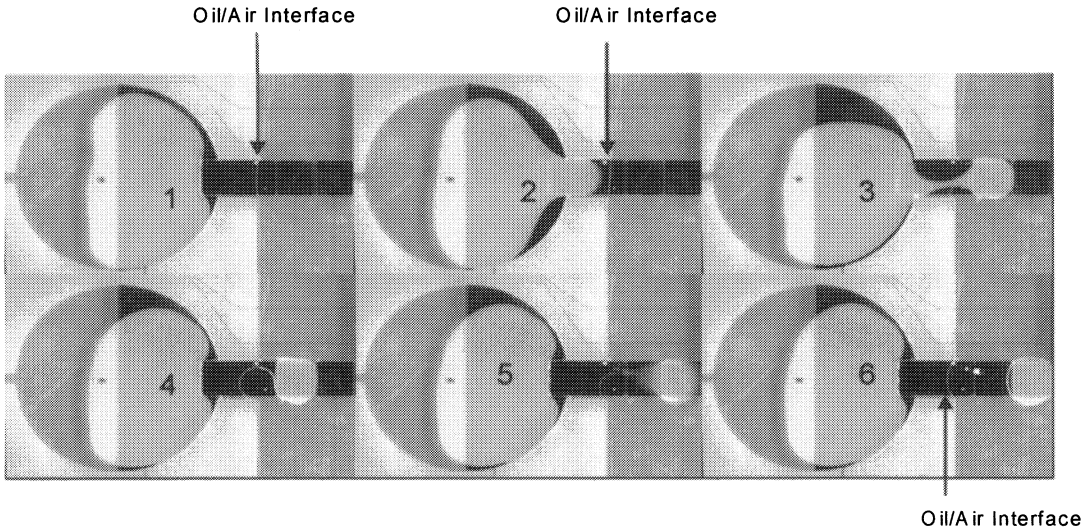

Figure 6. Dispensing a fluorescein droplet from an oil-confined reservoir across an oil/air interface: 1) droplet surrounded by silicone oil; 2) activation of dispensing electrodes; 3) droplet passes through the oil/air interface; 4-6) droplet breaks free from interface and transports in air.

3. APPLICATIONS

3.1 Attogram Particle Detection Air Sampling

Knowledge of size distribution of chemical constituents of ambient aerosol is of critical importance for understanding a multitude of environmental problems. Knowledge of aerosol chemical composition is essential to understanding the aerosol effects on climate and the environment in general. Chemical composition of aerosol particles controls many of their properties, such as their refractive index and affinity to water, both of which strongly affect light scattering by the aerosol and thus the direct aerosol effect on climate. Furthermore, information on aerosol chemical composition as a function of size is needed. Numerous measurement campaigns have been undertaken to measure aerosol properties and chemical composition both on the ground and using aircraft. [14-18] However, measurements of aerosol chemical composition, especially size segregated, still remain a daunting task.

Size-segregated chemical composition of aerosol is usually measured using cascade impactors, such as Micro-Orifice Uniform Deposit Impactors (MOUDI, MSP Inc.). In cascade impactors aerosol is collected on several stages with progressively smaller cut-off diameters. The aerosol is impacted on aluminum or Teflon filter substrates, which after collections are washed in ultra-pure water and the extract is analyzed. Because each of the preparation, sampling and analysis steps is manual, impactors require a large amount of manual handling to obtain one sample, which makes their

application extremely expensive. The high labor costs associated with the sampling make more than one measurement per location virtually impossible, thus sacrificing the quality and reliability of the measurements. In addition, each handling step introduces a risk of contamination. Impactors also have a low time resolution (several hours) which hampers their use on aircraft, which is central for understanding aerosol/cloud interactions.

Because of the very small volume of the extraction droplet in the scanning droplet collection surface, the resulting solution will be several orders of magnitude more concentrated than when "macro" methods of extraction are used (i.e. when the impaction substrate is washed with several milliliters of solvent). The higher concentration of the extract will allow a much shorter sampling times increasing the time resolution. The detection limit and/or minimum time resolution of the device is demonstrated with the following analysis. To obtain a meaningful measurement, sampling needs to be done long enough to produce a detectable concentration of the analyte in the extraction droplet. The concentration in the extract relates to the air concentration and the sampling time through the following equation:

$$C_w = \frac{C_a F_a t}{V_w} \tag{1}$$

in which C_w is the concentration the substance in the extract, C_a is the concentration of the substance in air, F_a is the sampling flow rate, t is the sampling time, and V_w is the volume (mass) of the extraction droplet. The detection limit in air is then:

$$LOD_{air} = \frac{LOD_w V_w}{F_a t} \tag{2}$$

in which LOD_{air} is the detection limit in air, and LOD_w is the limit of detection of the substance in the solution.

From Equation 2 it follows that the LOD in air is proportional to the LOD of the analytical assay and the extraction volume, while inversely proportional to the sampling flow rate and sampling time. It is the smaller extraction volume of the scanning droplet collector that make possible much shorter sampling times than the currently used manual method. The LOD of the analytical assays that are used are on the order of ppbm (part per billion mass), as will be discussed below. Even if it is assumed that the analytical LOD is of the order of 1 ppmm (part per million mass), it can be shown that even for a 1 minute sampling, a very low detection limit in air can be achieved. The sampling flow rate of MOUDI impactors is 30 L/min. If the volume of the extract is 1 µl (1 mg mass for water), then using Equation 2 it follows that these parameters lead to a detection limit of 33 ng/m^3 (33 attograms/µL - (10^{-18}g)) for each impactor stage. The time resolution can be increased at a cost of a proportional decrease in the detection limit.

Once sample collection is complete, the collection droplet is moved through an air/oil interface into the analytical section of the LoC. Target analytes are the major inorganic aerosol constituents: sulfate, nitrate, and ammonium. These compounds comprise the bulk of ambient water-soluble material. We have utilized electrowetting to demonstrate colorimetric enzyme-kinetic biochemical assays [11, 12] using a similar setup as shown in Fig. 1. To establish base-line, on-chip detection sensitivity for sulfate, nitrate, and ammonium, standard colorimetric assays will be used as the basis for reacting predetermined concentrations of analyte with reagents to produce colored complexes.

The droplets of the reagent and the analyte are merged by applying voltages to the appropriate electrodes. The merged droplet is further mixed by shuttling it across electrodes for 5 seconds at an actuation voltage of about 50 V. Our earlier results indicate that mixing should be complete in less than 3 seconds for a 2x4 pattern of mixing [9,10]. At the completion of mixing, the absorbance is measured using the LED (light emitting diode)/photodiode setup described earlier. All the reactions will be performed at room temperature. An example of absorption curves obtained from on-chip detection of glucose assays is shown in Fig. 7. [12] All assays are performed in a silicon oil medium with a top plate to preserve droplet volumes by preventing evaporation and eliminating contamination of droplet transport surfaces. Droplet transport in oil has been found to encase the droplets and to keep the contents of the droplets from depositing on the hydrophobic transport surface surface. [13]

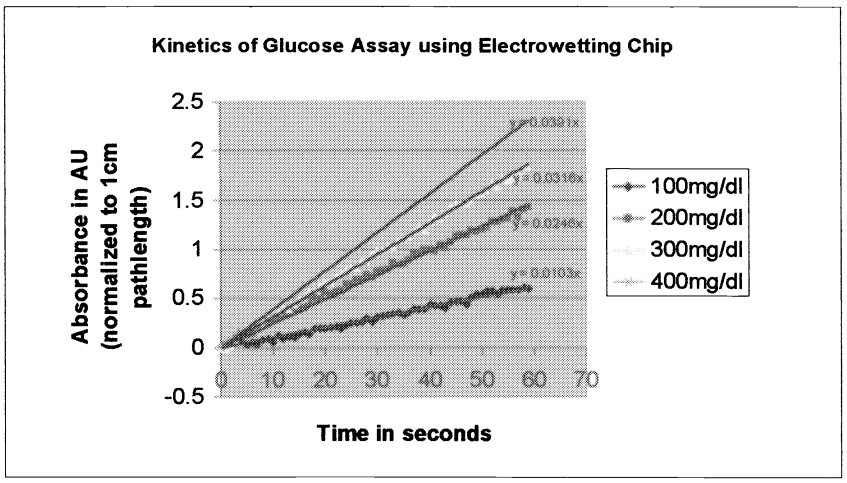

Figure 7. On-chip glucose assays showing linear response with concentration.

3.2 Attogram Explosive Partcle Detection

An estimated 100 million land mines buried in 65 countries throughout the world pose an enormous humanitarian problem, killing and mutilating thousands of civilians. The search and destruction of these mines remain the focus of humanitarian mine detection and removal primarily in Europe, Africa, Asia, and Central and South America. Even though the land mines may cost as little as $3 apiece, deactivation of a single mine can cost anywhere between $300 and $3,000. In addition to land mine detection, chemical detection of explosives is also needed to assess contamination of soil and water. Many munitions manufacturing and storage sites are contaminated with TNT (2,4,6-trinitrotoluene) as a result of manufacturing spills, unexploded ordnance, and disposal of explosive-contaminated wastewater. TNT poses a health risk to humans even at very low parts per billion concentrations in ground water [1]. It is suspected to be a carcinogen in addition to being highly toxic for humans, plants, and animals [2]. Therefore, TNT-contaminated environments need to be remediated. Thus, there is a significant unmet need for rapid, portable and on-site detection of land mines, unexploded ordinance, and soil contaminants.

Several commercial field screening test kits are available for the detection of TNT in soil and water. [19, 20] Colorimetric methods are also used to detect classes of explosives such as nitroaromatics, nitramines, and nitrate esters. These methods require manual sample extraction from soil samples and preconcentration for water samples. Further, calibration with a control solution needs to be performed *manually*, the sample and reagents have to be mixed *manually* by shaking, and the absorbance from a spectrophotometer has to be noted *manually*. Due to the discrete number of manual operations involved in the current colorimetric field analysis, one of the main disadvantages is that an experienced chemical analyst is required on-site.

An ideal on-site detection system would be inexpensive, sensitive, fully *automated*, reliable, and compatible with a broad range of samples. Microfluidic lab-on-a-chip (LoC) technology offers such a detection system due to the advantages in portability, reduction of the volumes of the sample and reagents, faster analysis times, increased automation, compatibility with mass manufacturing, and high throughput. Microfluidic capillary electrophoresis chips have been utilized for the detection of nitroaromatics such as TNT, DNT, NT, and DNB. [21-24] Most of the microfluidic detection methods, so far, have used electrochemical detection due to its inherent suitability for miniaturization and due to the good redox properties of nitroaromatics. Capillary electrophoresis chips can detect individual compounds of nitroaromatics (analtye-specific) while in current colorimetric methods, nitroaromatics are detected broadly (class-specific). However, none of these systems have addressed the sampling and collection of analyte particles.

The proposed digital microfluidic chip will be used to concentrate explosive particles by extracting airborne particles adsorbed on the collection surface described above. The concentrated analyte droplets will be quantitatively analyzed using either a colorimetric assay performed on the chip, or by an immunoassay. Assay solutions will be manipulated as discrete volumes, unlike the continuous flows conventionally used in other bio-molecular systems.

Preliminary results have been obtained from detecting commercial grade 2,4,6-trinitrotoluene (TNT) and pure 2,4-dinitrotoluene obtained from Sandia National Labs. [25] Assays were performed on an electrowetting chip in three steps: dispensing, electrowetting-enabled mixing, and colorimetric detection. Droplets of TNT and KOH were dispensed manually by a pipette on the electrowetting chip. These two droplets were merged by applying voltages to the appropriate electrodes. The merged droplet was further mixed by transporting the mixture, causing enhanced mixing flow. At the completion of mixing, the absorbance was measured using an LED. All the reactions were performed at room temperature.

The detection limit of the current on-chip method can be calculated from the measured results in Figure , assuming that the calibration or the reference reading is performed using only a single concentration. The lowest detectable concentration corresponds to the intercept of the linear fit on the y-axis, and any absorbance measured lower than this value would be reported as zero concentration of TNT. The detection limit of this method is therefore 0.0145AU/0.0056 $\approx$ 2.6μg/mL. This level is very competitive with TI's antibody-based competition assay detected using a surface plasmon resonance sensor (7.8μg/ml). If a cubic meter of sampled air contains 1μg of TNT (1femtogram/ml of air), and all of this particulate is collected on our sampling surface and concentrated in a 1μl droplet, then the droplet will contain a TNT density of 1μg/μl or 1000μg/ml, which is well above the detection limit of our assay. This means that detection sensitivities in the low attograms (10^{-18}g) of TNT/ml of air may be possible. This level is competitive with results obtained by Nomadics, Inc. with amplifying fluorescent polymers.

The absorbance spectrum of the color products resulting from the assays for TNT and DNT is shown in Fig. 9. It shows that the absorbance peaks of the colored complex formed by the reaction of TNT and DNT with KOH are mutually independent. This means that TNT could be quantitatively estimated even in the presence of DNT, which is common when dissolved in soil. To verify this hypothesis, mixtures of TNT and DNT were analyzed in various ratios on a spectrophotometer at 505 nm (absorbance peak of TNT). From this experiment, we confirmed that the absorbance at 505 nm is linear with TNT's concentration and is negligible for 100% DMSO and 0% TNT. Therefore, using this colorimetric reaction, TNT can be detected even in the presence of DNT. We have also performed preliminary studies on the colorimetric reaction of DNT with KOH in DMSO.

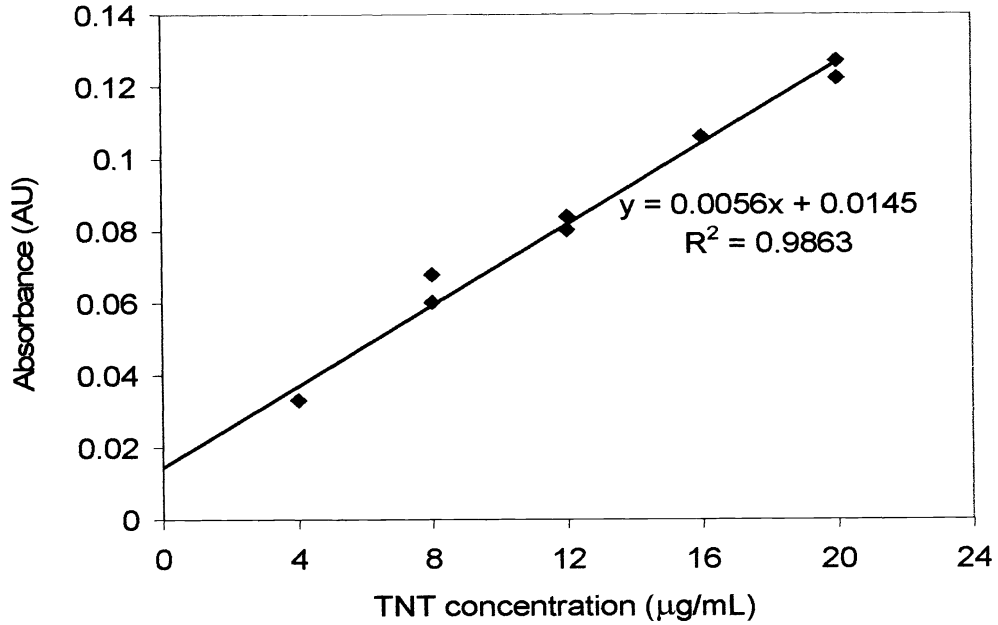

Figure 8. Calibration curve of absorbance with respect to the concentration of TNT demonstrating a linear relation on the electrowetting chip

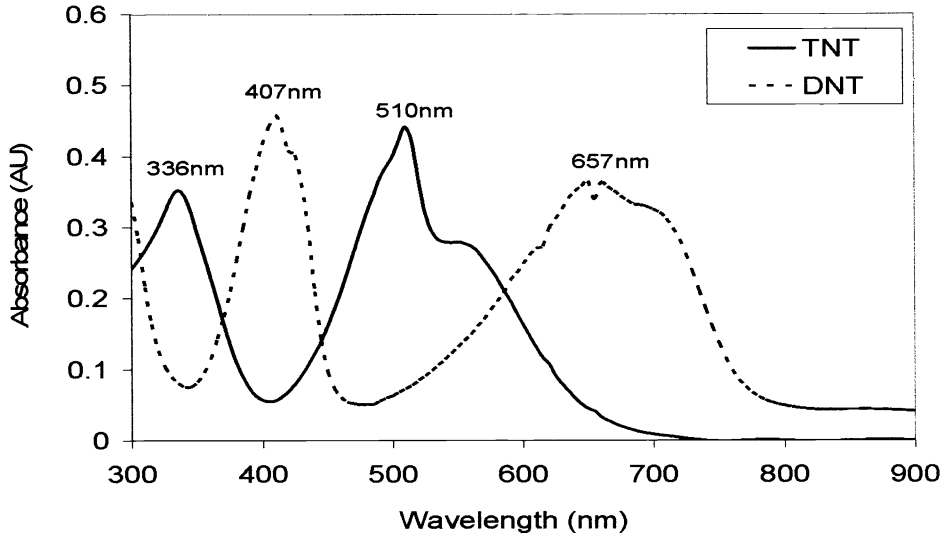

Figure 9. Absorbance spectrum of colored complexes formed in the reaction between TNT/DNT and KOH, using DMSO as the solvent.

4. CONCLUSIONS

A digital microfluidic LoC has been described with an integrated particle collection surface for quantitative size-segregated measurements of particulate in ambient aerosol with a time resolution of 1 minute and a detection limit that will allow its application even in clean "background" locations. The time resolution of the device is two orders of magnitude higher than that of the conventional cascade impactors used in aerosol sampling, allowing aircraft studies of aerosol plumes and aerosol/cloud interactions with unprecedented special resolution.

This instrument combines the proven technology of the Micro-Orifice Uniform Deposit Impactors (MOUDI) with a novel method of digital microfluidics. The aerosol is impacted directly onto the surface of the microfluidic chip that will be incorporated into a MOUDI. After a brief collection phase, the surface of the chip will be washed with a micro-droplet of ultra-pure solvent that will be digitally directed across the impaction surface, dissolving aerosol constituents. After the washing phase the droplet will be mixed with specific reagents that produce colored reactions with components of interest. The concentration of the analyte will be determined by measuring absorption at specific wavelengths using on-chip light-emitting diodes and detectors. After the analysis step the sampling cycle can be repeated. Because of the very small droplet volume used for aerosol extraction, the resulting solution is relatively concentrated and the substances can be detected after a very short sampling time (1 min). The on-chip colorimetric detection using digital microfluidics has been successfully demonstrated at concentration levels expected to be found under ambient sampling conditions.

The instrument described in this paper has the potential to be an invaluable tool in the studies of atmospheric aerosol and its effects on the environment, as well as in nitroaromatic explosive particle detection. Application of the proposed instrument also can be extended to detection of airborne bioagents.

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