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Technical note

# Ballpoint pen tips as robust cone-jet electrospray emitters

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ABSTRACT

This technical note documents the use of ballpoint pen tips as robust electrospray emitters. The embedded microsphere helps stabilize Taylor cones by effectively reducing the height of the liquid meniscus and significantly decreasing the viscous damping time of the Taylor cone. The microsphere also provides a mechanism for the Taylor cone to continuously adapt its base diameter to match the voltage applied. As a result, the ballpoint pen electrospray emitter noticeably expands the operation envelope in the flow rate-voltage space.



## 1. Introduction

Electrospray (ES) is a liquid atomization technique extensively used by the aerosol research community and beyond for generating relatively uniform micrometer and even nanometer sized droplets (Fenn et al., 1989; Chen et al., 1995). The ES emitter can be as simple as a metallic capillary with a blunt tip. Liquid with finite electrical conductivity is driven by a syringe pump or pressure difference through the capillary, which is charged at a few kV DC potential. Under intense electric stress, the liquid meniscus at the capillary tip may deform into a conical shape that is often termed as Taylor cone (Taylor, 1964), from which a fine jet erupts and subsequently breaks up into droplets. This most widely used and intensively studied mode of operation is called cone-jet electrospray (Cloupeau & Prunet-Foch, 1989; Tang & Gomez, 1994; Ganan-Ganan-Calvo et al., 1994).

Formation of a stable Taylor cone (Pantano et al., 1994) is critical for robust operation of cone-jet electrospray. An ideal ES emitter should meet the following requirements: (i) Large operation envelope in the $Q$–$V$ space, where $Q$ is the flow rate and $V$ is the voltage. This means the Taylor cone can be formed for a wide range of voltages and flow rates. (ii) Stable operation, which means the Taylor cone will not frequently change its height, or detach from the jet under various external disturbance such as mechanical vibration of the nozzle, changes in ambient gas flow around the nozzle, fluctuations in flow rate supplies, and intermittent wetting to the outside wall of the capillary. (iii) Robust, which means the emitter is not easily damaged or clogged.

To meet the first and second requirements, ES emitters (either in-house made or commercially available ones) tend to have very small tip diameter. For example, metal capillary emitter can be as small as 36 gauge (inner diameter of 35 μm and outer diameter of 110 μm) (Hu et al., 2013). Tip outer diameter can be further reduced to 1–10 μm using pulled glass capillary emitters. Although these fine emitters can generate stable Taylor cones, they are delicate to handle, prone to clogging, and relatively expensive. For these reasons, several alternative Taylor cone stabilizing strategies (other than simply

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reducing blunt capillary outer diameter) have been reported in the past, such as externally wetted solid tip (Lozano & Martinez-Sanchez, 2005), pointed hypodermic needles (Rebollo-Munoz et al., 2013), and sharp inserts at the nozzle tip (Sorensen, 1999; Sen et al., 2006).

In this Technical Note, we describe a type of robust emitter that is based on ballpoint (or roller ball) pens. Since its introduction in 1930s, ballpoint pens have evolved into an inexpensive ( < $1 apiece) and reliable writing tool. From the engineering prospective, the ingenious design of the ballpoint tip is essentially a heavily optimized device to reliably deliver volatile liquid solution (ink) at low flow rate. From the ink cartridge volume ( ~1 mL), writing length per cartridge quoted by the manufacturer ( ~5 km), and typical writing speed ( ~50 mm/s), one can estimate the flow rate is $<1$ μL/min, which a magnitude that falls in the flow rate range of many ES applications. Here we show that the ballpoint pen tip can be used as robust ES emitters with significantly expanded operation envelope in the $Q$–$V$ space.

## 2. Experimental setup

Figure 1 shows the scanning electron micrograph (SEM) of a few typical ballpoint pen tips with the microsphere (Fig. 1a) and the internal structures of the tip after the ball is removed (Fig. 1b and c). The microsphere is embedded in a matching housing socket, which forms a ball joint and the microsphere is free to rotate inside the socket. Remarkably, at the inner wall of the socket, three to five microfluidic channels for ink delivery are present. Similar microfluidic channels are found for all ballpoint pens with ball diameter ranges from 0.25 mm to 1.6 mm, although smaller ball point pens (0.25 mm for example) can accommodate only three channels (Fig. 1c). Although several ballpoint tips were tested, we only report the results for the 0.5 mm ballpoint because the results are similar for other sizes. The ES emitters are the metal tips which were removed from ballpoint pens ink cartridge by an applier. The tips were first thoroughly rinsed by DI water jet, and then cleaned by ultrasonic bath of water, ethanol, and acetone (10 min each).

The emitter was connected to a syringe by matching Teflon tubing. The emitter is also electrically connected to a high voltage DC power supply. The liquid (pure ethanol) was supplied by a syringe pump. A flat ground electrode was positioned about 5 cm away from the emitter. The droplet diameter of the spray was measured using Phase Doppler Interferometry or PDI (Artium). For each PDI measurement, we positioned the laser probe volume at the spray center axis. Such measurements give the size of the primary droplets, which account for dominant mass in a cone-jet electrospray. We took 10,000 primary droplet samples in each measurement and recorded the averaged droplet diameter $D_{10}$. The still images of liquid meniscus were recorded by a digital SLR camera (Canon 650D) and a 100 mm macro lens with 1:1 magnification. Videos of experimental phenomena were recorded with a high speed camera (Phantom v12.1) and a long working distance microscope lens. A collimated LED light source is placed behind the jet and pointed to the camera to form the shadowgraph configuration. The images were post processed (such as creating binary images) using ImageJ (NIH).

## 3. Results and discussion

Figure 2 shows the liquid meniscus morphology at different voltages at 0.5 mL/h. The image of a dry emitter (gray) was superimposed on the images of wetted emitter with electrospray (black). In this way a better visual representation of the liquid meniscus can be rendered. As the voltage increases, the liquid meniscus shrinks further and more closely anchors on the microsphere. The average diameter of primary droplets generated by flat tip emitter and ballpoint emitter is very similar (Fig. 3a). This is not surprising because the liquid jet is a result of singularity and the jet diameter is not affected by the much larger liquid meniscus. Jets with identical diameter will break up into droplets with same size.

To quantitatively describe the size of the meniscus, we choose the height of the cone as the characteristic length (Pantano et al., 1994; Ganan-Ganan-Calvo et al., 1996). The height $H$ is defined as the distance between the lowest position of the microsphere to the point where is the jet is attached to the Taylor cone (Fig. 3b insert). $H$ at several representative

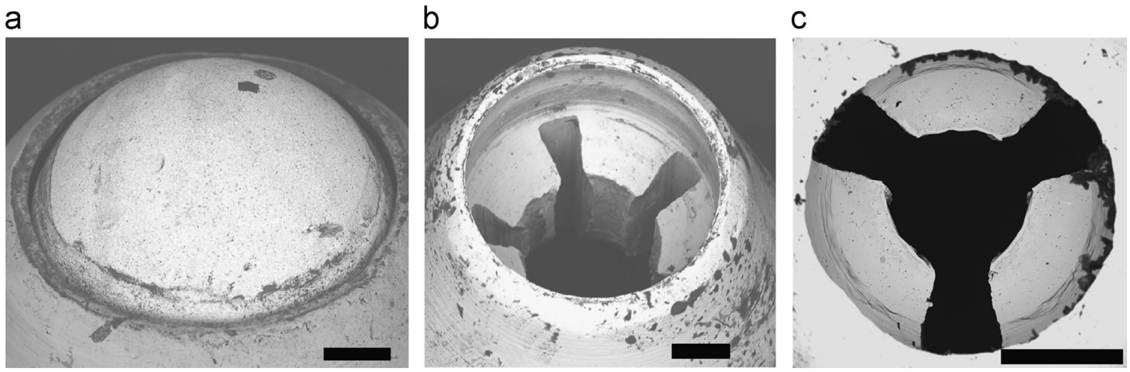


**Fig. 1.** SEM images of ballpoint pen tips. (a) Tip of a ballpoint pen with 0.5 mm in diameter; (b) the housing (with the ball removed) showing the microfluidic channels of 0.5 mm diameter ballpoint; (c) the housing of 0.25 mm ballpoint. Scale bars: 100 μm.