



Cite this: *Analyst*, 2018, **143**, 5918

Received 16th July 2018,
 Accepted 29th September 2018

DOI: 10.1039/c8an01322e

rsc.li/analyst

Dual purpose fibre – SERS pH sensing and bacterial analysis†

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The exploitation of fibre based Raman probes has been challenged by often complicated fabrication procedures and difficulties in reproducibility. Here, we have demonstrated a simple and cost-effective approach for sensing pH through an optical fibre, by employing a wax patterned filter paper-based substrate for surface enhanced Raman spectroscopy (SERS). Through this method, high reproducibility between fibres was achieved. In addition to sensing pH, it was possible to extract fluid samples containing *P. aeruginosa* for further analysis. This dual purpose fibre is bronchoscope deployable, and is able to gather information about both the host and pathogen, which may lead to an improved treatment plan in future *in vivo* applications.

Introduction

With the rising global challenge of antimicrobial resistance, there is an urgent need to reduce unnecessary antimicrobial prescriptions.¹ Ventilator-associated pneumonia (VAP) is the most common infection among the critically unwell in intensive care units (ICUs), with *Pseudomonas aeruginosa* behind many of these infections.²

Studies have shown that using the standard methods to identify the infectious agents, often by interpreting non-specific clinical or radiological features combined with culture techniques from sputum samples, was not adequate to diagnose lower tract respiratory infection but required processing of bronchoalveolar lavage fluid (BALF) samples.³ However, even the use of these samples has a number of limitations. Bacterial cultures typically take up to 3 days for results, but

specifically, these samples can suffer from a lack of sensitivity due to aspirated fluid being prone to contamination from the upper respiratory tract. Molecular sequencing methods such as polymerase chain reactions (PCR) can be overly sensitive, potentially leading to overtreatment of patients. Combined with poor sampling techniques, there is a significant impact on the treatment and management of patients.^{4–7}

The correct identification of pathogens causing respiratory infections and the monitoring of their antimicrobial sensitivity is of great importance. In addition to identification, knowing the physiological environment of the site of interest can also hold great value. pH is tightly regulated within cells and their microenvironments, with any deviations from the homeostasis indicating disease processes. Within the lung, an acidic pH can encourage the growth of bacteria, reduce the efficiency of endogenous cationic antimicrobial peptides and inactivate some antibiotics – all factors that contribute to antimicrobial resistance and worsening patient outcome.^{8,9}

The need for bed-side based monitoring has driven research efforts with a focus on robust and rapidly responding optical sensor devices. Fibre-based Raman spectroscopy is becoming a popular method for *in vivo* investigations due to its being a non-destructive and minimally invasive technique. Furthermore, it exhibits high spatial resolution and chemical sensitivity, important factors for *in situ* monitoring. However, as Raman scattering is an inherently weak phenomenon, its use for dynamic physiological sensing can be somewhat limited.

Surface enhanced Raman spectroscopy (SERS), where a reporter molecule is adsorbed on to the surface of a metal nanoparticle (NP), can increase the signal intensity by several orders of magnitude over conventional Raman scattering. SERS has been used in many applications, from intracellular physiological sensing, drug delivery sensing, explosive detection and many more.^{10,11}

SERS has been demonstrated through fibre previously, however, it has been challenged by difficulties in reproducibility from fibre to fibre, as well as generating SERS signal inten-

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†Electronic supplementary information (ESI) available. See DOI: 10.1039/c8an01322e



Here, we demonstrate a facile and cost-effective SERS substrate capable of ratiometrically measuring pH using SERS, whilst retrieving a biological fluid sample through combining paper and fibre-based systems. The advantages of a wax patterned paper sensing substrate are two-fold, it allows simple controlling of particle deposition and also facilitates an easy way to retrieve biological fluid samples. Our method has been designed to be small enough to be bronchoscope deployable with the ability to reach alveolar regions within the lung, allowing for site specific information to be gathered and so gaining information about both host and pathogen. This approach has also overcome many of the outlined challenges by achieving an easily repeatable fabrication process and generating high signal to noise ratios.

Paper SERS substrate design

4-Mercaptobenzoic acid functionalised AuNPs (4-MBA; 150 nm, 3.6×10^8 particles per μL) were pipetted on to filter paper substrates. Repeated depositions of a low volume of AuNPs (2 μL droplets) were applied, to a final volume of 2–8 μL , with drying stages in between, to avoid a loss of AuNPs through soaking and washing through the paper. The size of the spots that contain AuNPs was defined by the volume of the solution, however there is much variance in shape and the spread, or wicking, of the AuNPs within the spots (Fig. 1A, I).

In an effort to overcome the influence of non-uniform capillary wicking, and therefore the low reproducibility of using a filter paper-based SERS substrate, a hydrophobic wax surround was printed onto the filter paper. Solid wax printing is a simple, inexpensive, and quick method, amenable to mass production. Patterning paper with a wax surround allows control of the wicking action of aqueous solutions, confining the dispersion to the hydrophilic areas.^{18–20} By limiting the solution containing the AuNPs to a defined area, there is a reduction in variability in AuNP concentration at any point within the hydrophilic area. A substantial difference between applying AuNPs to filter paper with and without a wax barrier

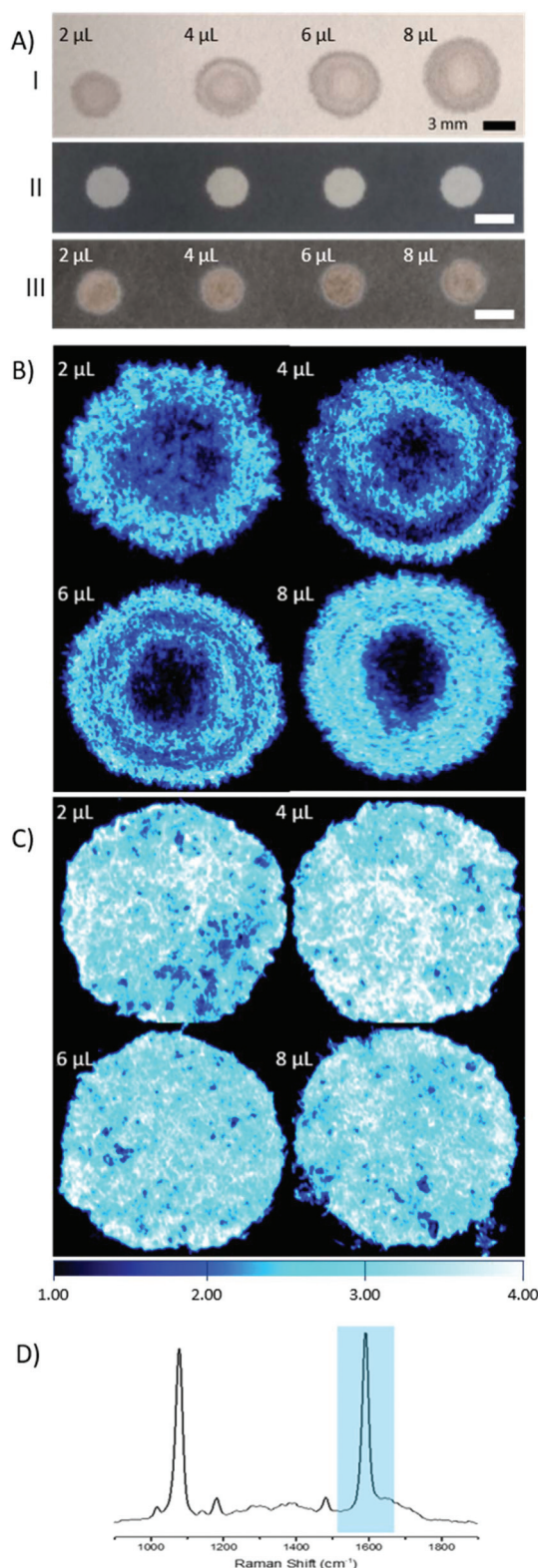


Fig. 1 Differences between filter paper with waxed boundary and no boundary. (A) I: AuNPs deposited onto filter paper without defined wax boundaries, II: images of filter paper with wax boundary, III: AuNPs deposited onto paper with defined wax boundary. All AuNPs depositions using 2 μL drops. (B) and (C) Raman intensity maps of filter paper and patterned filter paper (respectively), deposited with varying volumes of AuNPs. (D) SERS spectra of 4-MBA, with highlighted peak at 1587 cm^{-1} used for intensity comparisons.

Translation to fibre. While pH sensing using an optical fibre has been demonstrated previously,^{12,13} the background Raman scattering from the fibre is strong and can overwhelm the SERS signal from particles deposited on the distal end. Although some of these issues can be alleviated using sophisticated fibre designs, these are often bulky and require multiple fibres or fibres with large bores.^{12,21,22} Additionally, many

fibres for use with SERS sensing are prepared by dipping the distal end into concentrated nanoparticle solutions, leading to unknown and variable concentrations on the fibre tip.^{12,13,21,22} This has an impact on how reproducible, and therefore scalable, the production of the fibre sensors can be. Keeping in mind the future translation of fibre-based sensors into clinic, the ideal instrument would consist of a single fibre being bronchoscope deployable, with simple fabrication steps and minimal packaging requirements.

The fabrication of the packaged ferrule end is a simple process (Fig. 2A), whereby a 2 mm wide strip of the wax printed AuNP paper was placed, facing upwards, on a ring-shaped section of rubber. The ferrule was pushed through the ring with the paper flush across the top surface. A commercially available 200 μm single core (NA 0.39), multi-mode fibre was then threaded through the ferrule until abutted against the paper, and secured in place at the base of the ferrule.

Through combining the fibre with the paper-based SERS substrate, a controlled particle deposition is achieved, provid-

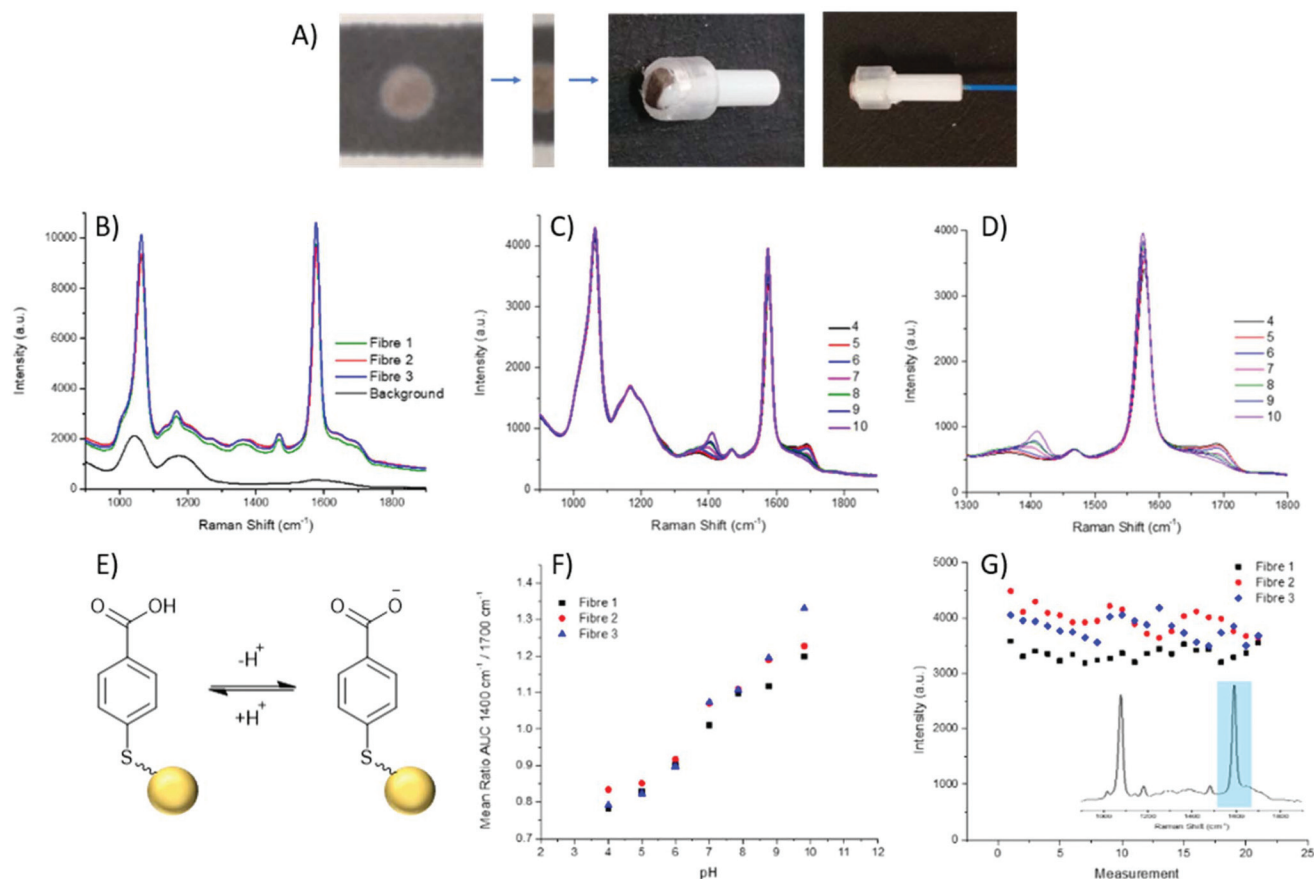


Fig. 2 (A) Process of fabrication to combine paper SERS substrate with 200 μm core optical fibre. Centre strip of AuNP paper cut and secured across a fibre ferrule, fibre threaded through and secured in place. (B) SERS spectra from 3 separate fibres, displaying similar signal intensities. Black spectrum represents intrinsic fibre background (which is easily overcome by SERS signals), 785 nm, 1 mW, 1 s integration time. (C) SERS spectra of 4-MBA, through fibre, over pH 4–10; (D) shows zoomed range of peaks of interest at 1380 cm^{-1} and 1700 cm^{-1} changing over pH 4–10. (E) NP-MBA nanosensors, equilibrium between MBA and its deprotonated form attached to a gold NP (yellow sphere, not to scale). (F) Ratio of Area under Curve (AUC) between 1380 cm^{-1} and 1700 cm^{-1} plotted against pH over 3 fibres. Each measurement was taken using 785 nm, 1 mW, 10 s integration time. (G) Intensity of 1587 cm^{-1} reference peak (inset) obtained during each measurement of the pH calibration plotted in chronological order.

ing confidence that the same signal intensity can be reached in any location where the fibre tip is placed on the AuNP paper. This extends to being able to reliably reproduce a strong signal when moving between fibres. Three separate fibres with packaged distal ends were prepared and their spectra recorded in air. It can be seen that across the three fibres reproducibility of the paper-based system is demonstrated by strong signals of similar intensities (Fig. 2B). Moreover, the strong signal intensity generated by the paper-based SERS sensor easily overcomes the intrinsic fibre background using relatively low laser power and integration time (1 mW and 1 s respectively). Importantly, the fibre background does not impose significantly on the pH sensitive peaks at 1380 cm^{-1} and 1700 cm^{-1} .

pH sensing. The reporter molecule, 4-MBA, has long been known as sensitive to environmental pH variations, and has been previously demonstrated as a suitable choice for biologically and clinically relevant pH sensing.^{11,12,23,24} The peaks observed at 1380 cm^{-1} and 1700 cm^{-1} are spectral features most dependent on pH. Under basic conditions (pH 9 and above), 4-MBA is known to be in the anionic form, affording a strong response in the 1380 cm^{-1} peak. Conversely, under acidic conditions (pH 5 and below), 4-MBA is mostly in the neutral form, generating a clear response in the peak found at 1700 cm^{-1} .

Aqueous pH buffers were prepared from pH 4–10 and verified with an electrochemical pH meter (Mettler-Toledo). The packaged distal end of the fibre was submerged in buffer and the spectrum recorded after 10 s. Between readings the AuNP-paper substrate was rinsed in dH_2O and blotted dry. Each fibre had three replicate calibrations where pHs were recorded in a random order. Three fibres in total were measured. The spectra were analysed by first normalising the spectra to the magnitude of a reference peak (1070 cm^{-1}), followed by evaluating the area under the curve (AUC) within a $\pm 25\text{ cm}^{-1}$ window of the peaks at 1380 cm^{-1} and 1700 cm^{-1} . Plotting pH against the AUC ratio, all fibres demonstrated consistent variation within the physiological range (Fig. 2F), again indicating the suitability of the paper SERS substrate for fibre sensing in future *in vivo* applications.

The loss of nanoparticles over time from the distal end of the fibre would be problematic, not only due to loss of signal, but also because loss of AuNPs is undesirable for use in *in vivo* applications. With the fibres which have been dip-coated with nanoparticles, typically, a porous sol-gel layer is used to protect the distal end. However, this coating can also suffer from variations in both coating depth and the porosity of the sol-gel layer, which may affect the speed at which measurements can be acquired. The paper SERS substrate showed no significant signal loss from over the course of the pH measurements (approximately 60 min per fibre). The intensity of the 1587 cm^{-1} peak was plotted over time, with the slight oscillations being attributed to the drying and wetting of the SERS samples. The average intensities between the first and last sets of pH measurements differ by less than 250 counts, less than 10% of overall signal intensity (Fig. 2G).

Extraction and culture of *P. aeruginosa*

There has been a considerable increase in the number of infections due to antimicrobial resistant bacteria with lower respiratory tract infections responsible for the second highest burden of disease globally.^{25–27} Within ICUs, the development of pneumonia is associated with high mortality rates.²⁸ The investigation of respiratory disease can involve biopsies, an invasive procedure, and the collection of BALF, which can become contaminated by bacteria found in the upper respiratory tract. The ability to sample fluid at specific sites can alleviate issues related to contamination. This fibre has been designed keeping in mind that it should be deployable through a conventional bronchoscope. In this way, it can be extended and retracted at specific region of interest, therefore minimising the contact between the distal end of the probe and upper respiratory tract.

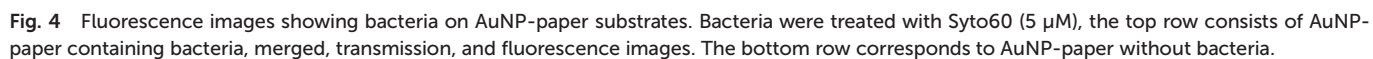
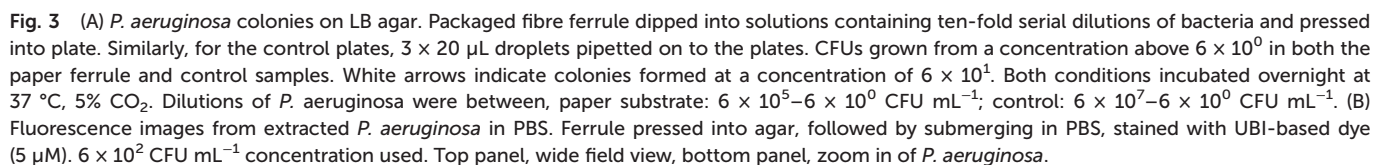
The porous nature of the filter paper not only provides a suitable substrate for the deposition of nanoparticles but also lends itself to retrieving a sample of fluid. We demonstrate that the filter paper is capable of sampling liquid containing bacteria which can then be cultured and counted. A clinical isolate of *P. aeruginosa* 3284 was cultured and prepared for this study.

Sample retrieval efficiency. To evaluate whether samples containing bacteria could be retrieved using this method, and to investigate the limit of detection, 10-fold serial dilutions of PA3284 ranging from 6×10^8 – 6×10^0 CFUs (colony forming units) per mL were prepared. The ferrule tip containing the AuNPs soaked paper substrate was dipped in to the bacterial containing solutions and gently pressed into lysogeny broth (LB) agar plates, with three presses per dip. This process was repeated a total of three times per dilution. After an overnight incubation period (37°C , 5% CO_2), the colonies were counted and compared to the control (consisting of $3 \times 20\text{ }\mu\text{L}$ droplets of each dilution) (Fig. 3). We observed a similar number of colonies between the paper and standard methods, with a LOD of 60 CFUs per mL in both the paper-based method and the Miles and Misra method, efficiently detecting below the clinical cut off (above 10^4 CFUs per mL to be considered pathogenic).^{4,29}

Direct imaging. We were able to further extract bacteria from the paper after pressing into agar by placing the paper strip in PBS ($500\text{ }\mu\text{L}$) and lightly vortexing. Using an in-house ubiquitin based bacterial stain ($5\text{ }\mu\text{M}$),³⁰ it was possible to image the live bacteria shortly after retrieval, without the need for a washing step, by confocal laser scanning microscopy (CLSM; Fig. 3B). Using bacteria specific probes enables the *in situ* optical detection of live bacteria in human alveolar lung tissue.^{30–32}

In addition, we investigated imaging bacteria directly on the paper itself (Fig. 4). Due to the autofluorescence of the paper (Fig. S2†), a far-red dye was used. The bacteria were labelled with a Syto60 ($5\text{ }\mu\text{M}$), a fluorescent nuclear stain, before introducing the AuNP-paper strips into the solution containing 6×10^5 CFUs per mL. While this strategy sup-





samples with an appropriate far-red bacteria-specific stain could enable *in vivo* bacterial detection on fibre without any need for a processing step. This could pave the way for simultaneous measurements for bacteria and pH through a single fibre.

Conclusions

Conflicts of interest

Acknowledgements

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