TITLE:

Quantitative SERS Detection of Uric Acid via Formation of Precise Plasmonic Nanojunctions within Aggregates of Gold Nanoparticles and Cucurbit[*n*]uril

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SUMMARY:

A host-guest complex of cucurbit[7]uril and uric acid was formed in an aqueous solution before adding a small amount into Au NP solution for quantitative surface-enhanced Raman spectroscopy (SERS) sensing using a modular spectrometer.

ABSTRACT:

This work describes a rapid and highly sensitive method for the quantitative detection of an important biomarker, uric acid (UA), via surface-enhanced Raman spectroscopy (SERS) with a low detection limit of ~0.2 μM for multiple characteristic peaks in the fingerprint region, using a modular spectrometer. This biosensing scheme is mediated by the host-guest complexation between a macrocycle, cucurbit[7]uril (CB7), and UA, and the subsequent formation of precise plasmonic nanojunctions within the self-assembled Au NP: CB7 nanoaggregates. A facile Au NP synthesis of desirable sizes for SERS substrates has also been performed based on the classical citrate-reduction approach with an option to be facilitated using a lab-built automated synthesizer. This protocol can be readily extended to multiplexed detection of biomarkers in body fluids for clinical applications.

INTRODUCTION:

Uric acid, which is the end product of metabolism of purine nucleotides, is an important

biomarker in blood serum and urine for the diagnosis of diseases such as gout, preeclampsia, renal diseases, hypertension, cardiovascular diseases and diabetes[1-5]. Current methods for uric acid detection include colorimetric enzymatic assays, high performance liquid chromatography and capillary electrophoresis, which are time-consuming, expensive and require sophisticated sample preparation[6-9].

Surface-enhanced Raman spectroscopy is a promising technique for routine point-of-care diagnosis as it allows selective detection of biomolecules via their vibration fingerprints and offers numerous advantages such as high-sensitivity, rapid response, ease of use and no or minimal sample preparation. SERS substrates based on noble metal nanoparticles (e.g., Au NPs) can enhance the Raman signals of the analyte molecules by 4 to 10 orders of magnitude[10] via strong electromagnetic enhancement caused by surface plasmon resonance[11]. Au NPs of tailored sizes can be easily synthesized as opposed to the time-consuming fabrication of complex metal nanocomposites[12], and thus are widely used in biomedical applications owing to their superior properties[13-16]. Attachment of macrocyclic molecules, cucurbit[*n*]urils (CB*n*, where *n* = 5-8, 10), onto the surface of Au NPs can further enhance the SERS signals of the analyte molecules as the highly symmetric and rigid CB molecules can control the precise spacing between the Au NPs and localize the analyte molecules at the center or in close proximity to the plasmonic hotspots via formation of host-guest complexes (**Figure 1**)[17-20]. Previous examples of SERS studies using Au NP: CB*n* nanoaggregates include nitroexplosives, polycyclic aromatics, diaminostilbene, neurotransmitters and creatinine[21-25], with the SERS measurements either being performed in a cuvette or by loading a small droplet onto a custom-made sample holder. This detection scheme is particularly useful to rapidly quantify biomarkers in a complex matrix with a high reproducibility.

Herein, a facile method to form host-guest complexes of CB7 and an important biomarker UA, and to quantify UA with a detection limit of 0.2 μM via CB7-mediated aggregations of Au NPs in aqueous media was demonstrated using a modular spectrometer, which is promising for diagnostic and clinical applications.

PROTOCOL:

1. Synthesis of Au NPs

1.1. Synthesis of Au seeds via the conventional Turkevich method[26]

1.1.1. Prepare 10 mL of 25 mM $HAuCl_4$ solution by dissolving 98.5 mg of $HAuCl_4 \cdot 3H_2O$ precursor with 10 mL of deionized water in a glass vial.

NOTE: Transfer a small amount of $HAuCl_4$ precursor into a weighing boat and use a plastic spatula instead of metallic spatula to weigh out the crystals because $HAuCl_4$ precursor will corrode metal labware. The weighing step should be performed as swiftly as possible, since $HAuCl_4$ is hygroscopic and will therefore increase its weight over time by absorbing water from the atmosphere. $HAuCl_4$ is highly corrosive and can cause severe skin burns and eye damage.

Take extra care when handling it.

1.1.2. Prepare 0.5 mL of 500 mM sodium citrate solution by dissolving 64.5 mg of sodium citrate powder with 0.5 mL of deionized water in a glass vial.

1.1.3. Dilute 1 mL of the 25 mM $HAuCl_4$ solution with 99 mL water in a 250 mL blue-capped bottle to give 100 mL of 0.25 mM $HAuCl_4$ solution.

1.1.4. Add 99.5 mL of the 0.25 mM $HAuCl_4$ solution into a 250 mL three-necked round-bottomed flask equipped with a condenser. Heat the solution to 90 °C under vigorous stirring and maintain the temperature for 15 min.

1.1.5. Inject 0.5 mL of the 500 mM sodium citrate solution into the reaction mixture and maintain the temperature and stirring until the color of the solution turns ruby-red.

NOTE: The reaction takes about 30 min.

1.2. Seeded growth of Au NPs via the kinetically-controlled method[13]

1.2.1. Cool the as-synthesized Au seed solution to 70 °C.

1.2.2. Prepare 10 mL of 60 mM sodium citrate solution by dissolving 154.8 mg of sodium citrate powder with 10 mL of deionized water in a glass vial.

1.2.3. Inject 0.67 mL of the 25 mM $HAuCl_4$ solution and 0.67 mL of the 60 mM sodium citrate solution to the Au seeds with a time interval of 2 min.

1.2.4. Repeat step 1.2.3 to gradually increase the size of Au NPs to 40 nm.

NOTE: It takes about 10 growing steps to reach 40 nm. The actual number of steps needed may be dependent on the precise set-up.

1.3. Seeded growth of Au NPs using automated synthesizer (Figure 2)

1.3.1. Transfer 25 mL of the Au seed solution prepared in section 1 to a 50 mL conical centrifuge tube and cool to 70 °C in a thermomixer.

NOTE: Monitor the temperature inside the thermomixer using a thermocouple thermometer placed in a 50 mL centrifuge tube containing 25 mL of water.

1.3.2. Fill a 3 mL Luer lock disposable syringe with 2.5 mL of 25 mM $HAuCl_4$ solution. Fill another 3 mL Luer lock disposable syringe with 2.5 mL of 60 mM sodium citrate solution.

1.3.3. Place the syringes in the syringe pumps and use Luer-to-MicroTight adapters to connect

the PEEK tubing (150 µm internal diameter) to the syringes. Insert the tubing into the centrifuge tube containing the Au seed solution in the thermomixer.

1.3.4. Set both syringe pumps to dispense 0.1675 mL of solution over 20 min (8.357 µL per min).

1.3.5. Set the thermomixer rotation speed to 700 rpm and press **Start** on the syringe pump containing the 25 mM $HAuCl_4$ solution.

1.3.6. After 2 min, press **Start** on the syringe pump containing the 60 mM sodium citrate solution.

1.3.7. 30 min after starting the $HAuCl_4$ solution injection, remove an aliquot of the Au NP solution for analysis.

1.3.8. Repeat steps 1.3.5 – 1.3.7 to gradually increase the diameter of the Au NPs up to 40 nm.

NOTE: This setup can be used to grow Au NPs up to 40 nm in one step by increasing the volume of reactants added in step 1.3.4. This is achieved by increasing the dispensing time whilst maintaining the same rate of injection.

2. Characterization of Au NPs

2.1. UV-Vis spectroscopy

2.1.1. Add 1 mL of the Au NP solution to a semi-micro quartz cuvette.

2.1.2. Turn on the spectrometer.

2.1.3. Set the wavelength range to 400 - 800 nm.

2.1.4. Acquire the UV-Vis spectrum for each sample.

2.2. Dynamic light scattering (DLS)

2.2.1. Filter the sample solution into a plastic semi-micro cuvette with a 0.22 µm filter.

2.2.2. Turn on the DLS instrument.

2.2.3. Set the temperature to 25 °C and equilibrate for 60 s.

2.2.4. Measure the hydrodynamic size of each sample.

2.3. Transmission electron microscopy (TEM)

2.3.1. Drop-cast a 5 µL droplet of the sample solution onto a C-coated 300-mesh Cu grid and dry in air.

NOTE: Dilution is needed for more concentrated Au NP solution samples to obtain well dispersed Au NPs on a TEM grid.

2.3.2. Acquire multiple TEM images for each sample using a TEM at 200 kV acceleration voltage.

2.3.3. Measure the diameter of 200 Au NPs for each sample using ImageJ to calculate the average size and standard deviation.

3. Formation of CB7-UA complexes

3.1. Preparation of 0.4 mM CB7 solution

3.1.1. Add 4.65 mg of CB7 to a 15 mL glass vial.

NOTE: The amount of CB7 is calculated based on the formula weight of CB7 (= 1163 Da) which has been employed by most reports in the literature. Nevertheless, CB7 solid samples typically contain water, HCl, methanol and other salts left from the synthesis and purification steps, contributing to ~10 – 20% dead weight in the sample. The trapped solvents and salts could not be removed by heating in a vacuum oven or other means. Their amounts vary between different batches of samples but can be quantified using elemental analysis. Yet, the presented protocol is not sensitive to the presence of unquantified amount of solvents and salts in the CB7 samples.

3.1.2. Add 10 mL of water to the vial and tighten the cap.

3.1.3. Sonicate the sample at room temperature until the CB7 solid is completely dissolved.

NOTE: CB7 was synthesized according to literature[27] but it is also commercially available.

3.2. Preparation of 0.4 mM UA solution

3.2.1. Add 2.69 mg of UA to a 50 mL centrifuge tube.

3.2.2. Add 40 mL of water to the tube and tighten the cap.

3.2.3. Use a thermomixer to swirl the sample solution by setting the temperature to 70 °C, speed to 800 rpm and time to 2 h. Allow the solution to cool to room temperature.

NOTE: UA has a low solubility in water (0.40 mM)[5]. Swirl for longer if the UA powder has not

been dissolved completely. Alternatively, ultrasonication can be used to facilitate the dissolution.

3.3. Sequential dilutions of the 0.4 mM UA solution

3.3.1. Dilute 5 mL of the 0.4 mM UA solution with 5 mL water in a 15 mL glass vial to give 10 mL of 0.2 mM UA solution. Tighten the cap and sonicate for 30 s.

3.3.2. Repeat step 3.3.1 using an appropriate amount of UA and water as described in Table 1.

3.4. Preparation of the CB7-UA complexes

3.4.1. Add 0.75 mL of the 0.4 mM CB7 solution and 0.75 mL of 0.4 mM UA solution into a 1.5 mL tube. Secure the lid and sonicate for 30 s.

3.4.2. Wait for 30 min to ensure the formation of host-guest complexes.

3.4.3. Repeat step 3.4.1 – 3.4.2 using UA solution of different concentrations.

4. SERS sensing of UA

4.1. Experimental set-up of the Raman system (**Figure 3**)

4.1.1. Switch on the 633 nm He-Ne laser (22.5 mW).

4.1.2. Switch on the modular Raman spectrometer.

4.1.3. Switch on the computer and start the software.

4.1.4. Click the **Spectroscopy Application Wizards** Icon, and then select **Raman**.

4.1.5. Start a new acquisition. Set the integration time to 30 s, scans to average to 5 and boxcar to 0.

4.1.6. Store background spectrum and enter the laser wavelength (i.e., 633 nm).

NOTE: Integration time is the time for each scan, scans to average is number of scans averaged to create each spectrum and boxcar is the number of neighboring pixels averaged[28].

4.2. Formation of the SERS substrates

4.2.1. Add 0.9 mL of the 40 nm Au NP solution and 0.1 mL of the pre-formed CB7-UA complex solution into a 1.5 mL tube. Secure the lid and sonicate until the solution changes from ruby-red to purple.

NOTE: Commercial citrate-stabilized 40 nm Au NP solution samples can also be used. Typically, the optical density of the localized surface plasmon resonance (LSPR) peak is adjusted to 1 via dilution from concentrated stock solution samples. Citrate concentration in the sample is typically kept as 2 mM.

4.2.2. Transfer the sample solution to a semi-micro cuvette. Place the cuvette into the Raman sample holder and close the cover.

4.2.3. Start the measurement.

4.2.4. Set up the auto-saving to record five consecutive SERS spectra.

4.2.5. Stop the measurement and change the sample.

4.2.6. Repeat step 4.2.1 – 4.2.5 using CB7-UA solution of different concentrations.

NOTE: Aggregation time is found to be dependent on the concentration of UA in the nanoaggregates, ranging from 30 s for 0.1 μM UA to 30 min for 20 μM UA, owing to the difference in the concentration of empty CB7 which has major contribution to mediating the aggregation of Au NPs. For the CB7-UA complex, one portal is blocked by the bulky UA molecule, rendering it unavailable for binding to the Au NP surface and therefore unable to mediate the NP aggregation[21]. The sample is ready for measurement when the color of the solution changes from ruby-red to purple.

5. Data analysis

5.1. Data processing

5.1.1. Download and install the baseline with asymmetric least squares (ALS) plugin into Origin.

NOTE: The ALS plugin requires OriginPro.

5.1.2. Insert the raw data into Origin.

5.1.3. Calculate an average value from the five SERS spectra of each sample. Divide the value by the power of the laser (i.e., 22.5 mW) and by the integration time (i.e., 30 s).

5.1.4. Click the **ALS** icon to open the dialog. Set the asymmetric factor to 0.001, threshold to 0.03 %, smoothing factor to 2 and number of iterations to 20 to correct the baseline of each averaged spectrum.

5.1.5. Plot the SERS spectra of different UA concentrations using stacked lines by y offsets. The

output should be intensity (counts s^{-1} mW^{-1}) against Raman shift (cm^{-1}).

REPRESENTATIVE RESULTS:

In the presented Au NP synthesis, the UV-Vis spectra show a shift of the LSPR peaks from 521 nm to 529 nm after 10 growing steps (**Figure 4A,B**) while the DLS data shows a narrow size distribution as the size of Au NPs increase from 25.9 nm to 42.8 nm (**Figure 4C,D**). The average sizes of G0, G5 and G10 measured from TEM images (**Figure 4E**) are 20.1 ± 2.1 nm, 32.5 ± 2.3 nm and 40.0 ± 2.2 nm respectively, with 200 particles counted in each case. These results indicate this protocol is effective in synthesizing uniform and narrowly dispersed Au NPs.

In the presented SERS studies, host-guest complexes of CB7 and UA were formed with empty CB7 mediating the formation of precise plasmonic nanojunctions within the Au NP: CB7 nanoaggregates, as supported by the characteristic UA signals in the SERS spectrum (**Figure 5A**). The assignments for the Raman peaks of CB (marked by +) and UA (marked by *) are shown in **Table 2**. Conversely, no SERS signals of UA can be observed in the absence of CB7, illustrating the key role of CB7 in triggering the aggregation of Au NPs.

A constant CB7 concentration of 20 μM was used in the SERS titration of UA throughout so as to ensure the in situ formation of reproducible plasmonic nanostructures (i.e., SERS substrates). The high sensitivity of the detection scheme presented in this protocol was demonstrated by the observation of clear SERS signals from the UA peaks at 640 cm^{-1} and 1130 cm^{-1} (attributed to skeletal ring deformation and C-N vibration respectively) down to ~0.2 μM (**Figure 5B–D**), which is known as the detection limit. In addition, very strong correlations (R^2 > 0.98) between the SERS intensity and log concentration of UA were obtained by power law for both peaks, with linear regions found in the range of 0.2 to 2 μM (**Figure 5E,F**). It should be noted that linear correlations between the SERS intensity and log concentration can be approximated for a narrow range of analyte concentrations, whereas the SERS signal approaches 0 when the log concentration approaches negative infinity (i.e., the analyte concentration approaches 0), as observed in our data. The SERS signals are also highly reproducible as evidenced by the small error bars shown in **Figure 5E,F**.

FIGURE AND TABLE LEGENDS:

Figure 1: Schematic illustration of the precise plasmonic nanojunctions within self-assembled Au NP: CB7 nanoaggregates. Inset shows a zoom-in of the plasmonic nanojunctions where the aggregation is mediated by empty CB7 while UA is enriched on the surface of Au NPs via host-guest complexation. It is noted that the scheme is not drawn to scale.

Figure 2: (a) Schematic illustration and (b) photograph of the automated Au NP synthesizer.

Figure 3: Schematic illustration of the Raman system.

Figure 4: Representative characterization of Au NPs. (**A**) UV-Vis spectra of Au NPs and (**B**) zoom-in spectra showing the shifting of the LSPR peaks as the number of growing steps increases to 10. (**C**) Hydrodynamic size of Au NPs and (**D**) corresponding plot of particle size as a

function of number of growing steps. (**E**) TEM images of Au NPs, showing sizes of Au seeds and Au NPs after 5 and 10 growing steps.

Figure 5: Representative SERS results of UA detection within Au NP: CB7 nanoaggregates. (A) SERS spectra of UA in the presence or absence of CB7. Raman peaks of CB7 and UA are marked by + and * respectively. (B) Full-range, (C) 600 - 700 cm^{-1} zoom-in and (D) 1100 - 1180 cm^{-1} zoom-in SERS spectra of UA with concentrations from 0 to 20 μM. Main Raman peaks of UA are marked by *. Spectra were baseline corrected and offset for clarity. (E,F) Corresponding plots of the SERS peak intensity against concentration of UA.

Table 1: Sequential dilutions of UA solution.

Table 2: Assignments for the Raman peaks of CB7 and UA[2,4,29].

DISCUSSION:

The automated synthesis method described in the protocol allows Au NPs of increasing sizes to be reproducibly synthesized. Although there are some elements that still need to be carried out manually, such as the fast addition of sodium citrate during the seed synthesis and checking periodically to ensure that the PEEK tubing is secure, this method allows Au NPs of large sizes (up to 40 nm), which would usually require multiple manual injections of $HAuCl_4$ and sodium citrate, to be synthesized via continuous addition over a long period of time.

Further characterization can be performed to elucidate the fundamental property of the CB complexes. For instance, the formation of host-guest complexes can typically be confirmed using ^1H nuclear magnetic resonance (NMR), which should show upfield shift and broadening of signals in case of complexation[21,22,25]. Yet ^1H NMR is not applicable to UA due to its lack of non-exchangeable protons. Alternative techniques such as ^{13}C NMR and mass spectrometry could also be employed to characterize the complexation. Binding constants between CB7 and UA can be measured using titration techniques, such as UV-Vis spectroscopy titration and isothermal titration calorimetry (ITC)[21,22,25]. Meanwhile molecular modelling based on force-field and density functional theory (DFT) models can be computed to obtain theoretical insights into the binding geometry of the host-guest complexes[21,22,25,29]. Moreover IR and Raman spectra can be computed by frequencies calculations[21,25,29].

SERS is a highly sensitive and selective analytical technique which allows identification of trace analytes via their molecule-specific vibrational fingerprints. SERS is gaining interests across different science disciplines, in particular biomedical studies, due to its greatly enhanced signals, much shorter acquisition time and high tolerance to liquid water (suitable for sensing in biofluids)[30-35]. In contrast to previous reports on UA sensing[1-4,36,37], the rigid structure of CB7 defines precise spacing of 0.9 nm between Au NPs via carbonyl portal binding while the surface-bound CB7 can trap UA molecules within its cavity (**Figure 1**), resulting in strong and localized plasmonic hotspots, and hence the highly sensitive (down to ~0.2 μM) and reproducible (within 2% error) SERS signals of UA with very strong correlations ($R^2 > 0.98$) between the SERS intensity and log concentration (**Figure 5**).

In an attempt to optimize the concentration of CB7, we note that 20 μM CB7 was used to ensure the formation of reproducible SERS substrates. In particular, the absolute concentration of CB7 used is dependent on the overall system (i.e., Au NPs, analytes and background molecules, if any)[18,22]. A higher concentration of CB7 should be used if the aggregation of Au NPs is too slow. Conversely, a lower concentration of CB7 should be used if the sample solution precipitates quickly and leads to shorter measurement windows. The aggregation of Au NPs mediated by CB7 in our experimental setting is expected to follow the diffusion-limited colloidal aggregation (DLCA) kinetics[19], in which open and elongated chain-like structures were rapidly formed initially before joining together as quasi-fractal network. DLCA kinetics typically occurs at a high CB: Au NP ratio (by number), which is equal to 10^6:1 in our case. It should be noted that uric acid is present in bodily fluids (e.g., blood serum, urine) at a higher concentration. For instance, the normal concentration of uric acid is 3.5 – 7.0 mg/dL in blood serum[38] and 16 – 100 mg/dL in urine[2] respectively (concentration above or below the normal concentration is known as hyperuricemia and hypouricemia)[39]. Therefore, only a very small amount of sample is needed for biomarker detection in this highly sensitive scheme where a high dilution factor is used to lower the concentration of the sample to a suitable range. This is particularly important for point-of-care monitoring of terminally ill patients whose urine excretion is very low. Highly diluted samples result in larger sample volumes and thus reduce errors in the quantification of biomarkers due to water evaporation and loss of samples due to liquid transfer, while giving other advantages including minimizing the matrix effects[25]. Due to the selective nature of this probing method, it is limited to analyte molecules that can form host-guest complexes with CB. It should be noted it is possible to observe interferences from other molecules because CB can bind to different guest molecules. Nevertheless, sample purification such as gel electrophoresis and HPLC can be performed prior to SERS measurement.

The detection scheme demonstrated in this protocol has the potential for multiplexed detection of biomarkers in a complex matrix for clinical applications when it is coupled to advanced data analysis techniques.

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DISCLOSURES:

The authors have nothing to disclose.

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