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Development of the Smartphone-based Colorimetry for Multi-analyte Sensing Arrays

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Here we report development of a smartphone app (application) which digitizes the colours of the colorimetric sensor array. A conventional colorimetric sensor array consists of multiple paper-based sensors, and reports the detection results in terms of colour change. Evaluation of the colour changes is normally done by naked eyes, which may cause uncertainties by the personal subjectivity and the surrounding conditions. Solutions to it have been severally sought in smartphones as they are capable of spectrometric functions. Our report specifically focuses on development of a practical app for the immediate point-of-care (POC) multi-analyte sensing without additional devices. First, the individual positions of the sensors are automatically identified by the smartphone, second, the colours measured at each sensor are digitized based on the correction algorithm and third, the corrected colours are converted to concentration values by the pre-loaded calibration curves. All through these sequential processes, the sensor array taken in a smartphone snapshot undergoes the laboratory-level spectrometry. The advantages of the inexpensive and convenient paper-based colorimetry and the ubiquitous smartphone are tied to achieve the ready-to-go POC diagnosis.

Introduction

Smartphone-based analysis is an emerging technique that provides the ideal platform for the point-of-care (POC) technology.[1] Being coupled with the everyday-technology, portable chemical analysis and immediate medical diagnosis can be conducted at a high level of accuracy with a little additional effort and cost. Potentially, everybody's low-cost POC test is expected to be realized based on the smartphone.[2] This report describes a way for the multi-analyte colorimetric POC test running on the smartphone.

The POC technology has been a rising issue in the field of chemical analysis and medical testing in the recent decades because it is simple to use and reports on-site results of the analysis or diagnosis. The best advantage of this technique is found in the convenience of use. The devices are compact and portable in hand so that it can be used whenever and wherever testing is needed. Another benefit of the POC technology is that the immediate results enable patients and clinical units to decide rapid decision and do on-site treatments. On demand for POC tests, there have been invented many kinds of POC methods[3] such as blood testers detecting glucose,[4] haemoglobin,[5] HbA_{1c}[6, 7] so on. Also, virus, drug, pathogens in food can be screened by small POC kits.[8-10]

Recent development of the POC technology requires smaller, simpler and cost-saving methods to satisfy everybody in using it without technical and economic barriers. The most probable candidate is the paper-based (including paper-like material) colorimetric method[11, 12] such as pH test paper and urine testers. A POC testing is done simply by a piece of the functionalized paper which senses analytes and reports the signals as colours readily read-out by the naked eyes.[4] The paper kit is cheap to purchase, light to carry and convenient to use. However, such benefits come with cost, which is subjective uncertainty in evaluating colours by naked eyes. Generally, human sensibility is considered to as be quite accurate, however at the same time, is subjective by personal and surrounding conditions, which brings about uncertainties.

Inheriting the advantages and overcoming the disadvantages of the paper-based colorimetry, scientists have tried to utilize spectroscopic methods to quantify the colour changes.[13] Since conventional spectrometers cannot make a full use of the proximity of the paper-based colorimetry, many people have looked for alternative approaches in smartphones. There are

many publications on use of smartphones as colorimetric sensors. As a smartphone has a built-in camera of high resolution, colorimetric data are acquired as a digital image which in turn are converted to analyte concentrations.[14] Because the smartphone replaces cumbersome spectrometers and the apps have user-friendly interfaces, even an untrained person can carry out tests at any situation. The smartphone-based colorimetry is acknowledged as an innovating technology, and variable applications are under development.[1, 15] As the smartphone only takes digital images through the camera, it has to resort to specially designed additional accessories. For example, opto-mechanical hardwares were designed for blood analysis where haemoglobin and cholesterol concentrations and red and white blood cell densities are measured.[16, 17] Another devices were invented for testing Albumin in blood and H^+/Na^+ in sweat and saliva[18] and for monitoring chemicals in water.[19-21] A commercial urine strip reader is already available in the market.[22] In those works, customized mechanic units were installed upon the existing camera. Even simpler methods were proposed to directly measure the colours without being aided by the additional mechanics. Concentrations of H^+ were measured by taking a picture of pH test paper.[15, 23] In these works, the colour changes of the paper were detected by capturing the image and evaluated by digitizing the colours with the standard colours provided by the reference charts. Even though the ambient light makes colours digitized differently according to the light conditions, the reference chart compensates the difference to yield correct values reducing errors originating from the light conditions. This paper-based method just needs a few pieces of paper for analysis and removes mechanical units attaching onto the smartphone.

Even though this stand-alone smartphone-based colorimetry application can provides the analysis platform closer to the ideal POC test, it possesses restrictions in practical usage. First, it should come with the reference colour chart because the analytical values are obtained from comparison of the target colour with the reference ones. Maybe the reference colours or their calibration curves can be pre-loaded on the smartphone for immediate use. However, the colours can be digitized differently upon the light source and the surroundings, so that comparison with the pre-loaded colours is not made properly. Another limitation is found when multiple analytes are tested on a single digitized image. Detection of different analytes on each sensor will be problematical because each sensor has its own reference colour chart. When the analytes are many, one picture may not have enough area to contain the paper-based sensors and all the reference colour charts. The third restriction is that the image should be captured at the designed angle and position to successfully recognize the colours at the sensors and the reference chart. The image mis-located or taken with shake can fail to collect the colours at the appointed positions. As an image has a limited space, much care is needed to exactly locate the sensors and the reference in a picture, especially when many analytes are measured. If we take into account that medical POC end-users are mostly patients and untrained people, the smartphone-based POC should be done based on snapshot-captured images.

Overcoming those problems, here we propose an advanced smartphone-based colorimetric method for multi-analyte diagnosis, where the calibration curves made from the reference colour chart are pre-loaded so that no reference colour needs to be taken with the samples, and the locations of the samples are automatically recognized by the pattern of the sensing array so that an untrained person is able to carry out POC diagnosis with little care. Eventually, a quick snapshot of the sensor array directly reports the diagnostic results. To prove the concept of our smartphone-based method, we use a commercially available urine test strip consisting of 12 paper-based sensors. The paper-based sensors, detecting specific chemicals and biomaterials respectively, are placed periodically in one array on a plastic substrate so that the multi-analyte sensing is monitored rapidly and simultaneously.

Theoretical consideration

Automatic recognition of the paper-based sensors.

As mentioned above, the smartphone-based measurement should be as easy as even untrained patients can operate by minimizing the restriction factors. Considering that the purpose of the smartphone-based measurement is simple POC diagnosis for patients and old people, not delicate examination for medical experts, the operation to obtain the digitized image of the sensor array should be done with little care. Instead of manually addressing the sensors or positioning them to the reserved locations, the smartphone should find the multiple sensors and digitize their colours by itself. To that achievement, we develop the automatic recognition procedure to find the sensors when a picture of the sensor array is taken. Therefore, even a clumsy snapshot can be readily processed to acquiring colours of the sensors.

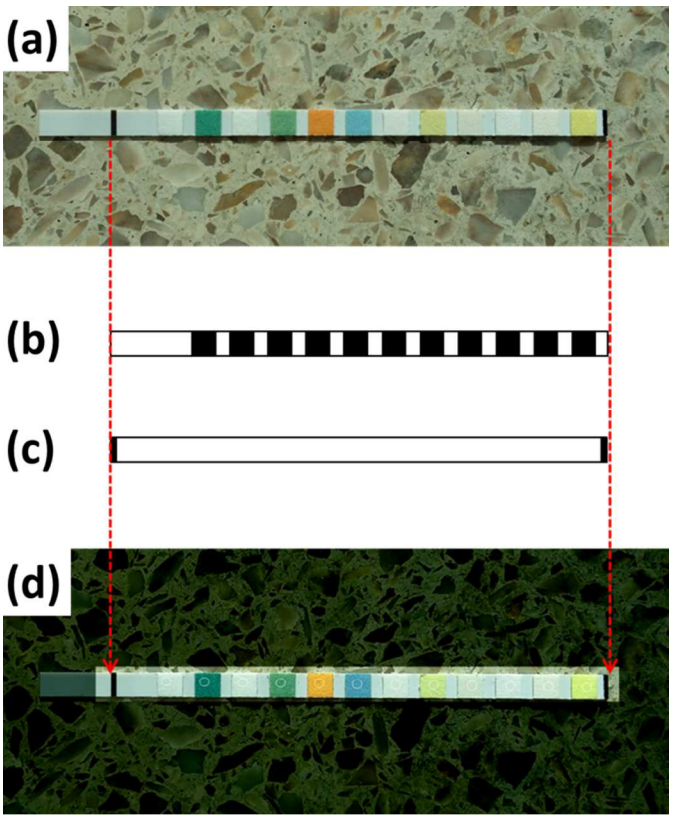

Fig. 1. (a) An optical image of a urine strip consisting of 12 paper-based sensors in array, (b) the mono-colour template to be projected on the optical image to estimate the position of the sensor array, (c) the second mono-colour template to be used to find the dimension of the sensor array and to identify the positions of each sensor, and (d) the image resulting from the automatic recognition, which activates only the sensor array and indicates the positions of the digitized colour by the circle marks

Fig 1 shows a typical sensor array consisting of 12 sensor pads, which detect the urine colour, ascorbic acid (vitamin C), leucocytes, specific gravity, pH, glucose, nitrite, protein, ketones, urobilinogen, bilirubin and red blood cells (RBC) in urine, respectively from the left to the right. What makes it special for the automatic recognition are the periodic pattern and the two black bars drawn at each end on the normal array. The process starts with roughly finding the position of the array using the mono-colour template which is made upon the periodic pattern of the array in Fig 1(b). The template match algorithm is following: when the camera is on, it monitors the screen with converting it to a highly contrasted mono-image with an appropriate threshold level. Then the pre-made template is projected upon the mono-image with scanning pixel by pixel and the most probable position is estimated. However, the exact position of each senor may be failed to be found because most probable position is only estimated. To complete it, the two black marks are utilized to find the exact position and dimension of the array when this second template is projected on the more highly contrasted mono-image as shown in Fig 1(c). Based on the dimension, the positions of the sensor papers are addressed by the smartphone.

The recognition process divides the smartphone screen into three parts. One is the area outside of the array, which is referred to the region-of-no interest. Subtracting this region from the original picture, the smartphone selects the region-of-interest (ROI) for rendering the post-processing. Fig 1(d) shows the result where only the ROI is activated and the rest is shaded out, therefore users can perceive if the array is properly identified. The ROI is again divided into two parts: the sensors and the background. The sensing signals are measured from the colours of each sensor pad on the array and the background signal is obtained from the black bar and the white substrate. These background signals are used for the colour correction.

In the previous reports,[15, 22, 23] the reference colour chart was taken with the sensors to make the calibration curve on which the colours were converted to analytical values. However in the present report aiming at convenient usage, only the sensor array is taken as a picture and the colours are converted to analytical values based on the pre-loaded calibration curves. Thus, in order to appropriately applying the pre-loaded calibration curves to the measured colours in the smartphone, we set the black and white colours of the background as the reference. The red (R), green (G), and blue (B) colours of the black and white background are used as the offset and the scale bar. All the sensing signals are adjusted with respect to each RGB values of the background signals by Eq 1.

$$R_{\mathrm{corr}} = \left(\frac{256}{R_{\mathrm{W}} - R_{\mathrm{B}}} \right) \left(R_{\mathrm{meas}} - R_{\mathrm{B}} \right), \qquad \text{Eq (1)}$$

where R_{corr} is the corrected value, R_{W} the white background value, R_{B} the black background value, and R_{meas} the measured value of the sensor, respectively. Then, the corrected RGB values become ready to be applied to the pre-loaded calibration curves. This is similar to the reference electrode and the *iR* drop compensation used to compare the electrochemical potentials which are obtained in different electrochemical systems.[24]

Conversion of the corrected RGB colour to analytical values.

In some literatures on the smartphone-based measurement,[19, 20, 25, 26] the RGB values of the digitized image are related directly to analytical values in terms of light intensity. However, it is not always effective because the composition of R, G and B making one digitized colour does not change monotonically with spectral wavelength and intensity.[27] Due to that fact, alternative colour spaces are sometimes used such as HSV and CIE 1932.[15-17, 23, 28] In this report, we deal with multiple analytes which display different colours or intensities of specific colours, so we need to show the analysis results as spectral data rather than the simple RGB values. As frequently seen in spectroscopic studies, the spectral change can be sorted into two types: the changes of wavelengths and intensities. Due to the difficulties to relate the RGB colours to spectroscopic changes, the HSV colour space is preferred in our report.

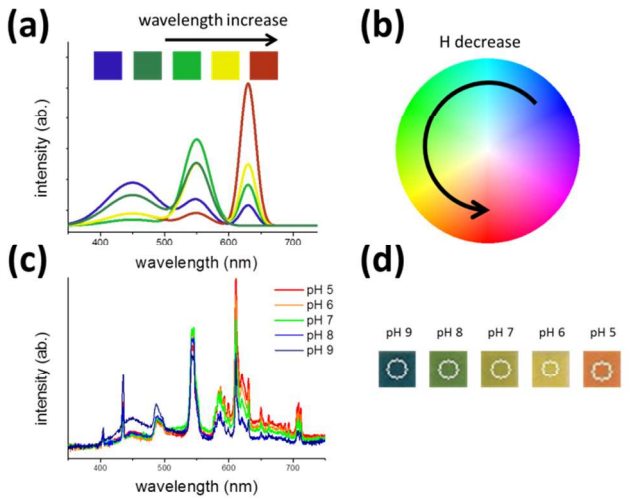

Fig. 2. (a) The colours of the five squares are made by mixing RGB colours at the ratios of R:G:B=2:1:7, 0:5:5, 1:7:2, 3:5:2 and 7:2:1, respectively. Their spectra are simulated by mixing each RGB spectra with the same ratios of the displayed colours, where the R, G and B spectra have wavelengths of 630, 550 and 450 nm, respectively.[13] (b) On the colour space, the arrow indicates the direction of the H decrease going along with the wavelength increase. (c) The spectra and (d) the optical images were measured on the pH paper sensors at different pH values.

The smartphone camera senses only three RGB colours and they have specific wavelengths, around 630, 550 and 450 nm, respectively. The observed spectral change results from the change of the relative ratios of the three colours rather than actual spectrum wavelength change. Unfortunately, the relative ratio does not go along with the spectrum wavelength as depicted by Fig 2(a). However, on the colour space of HSV, the hue (H) value monotonically changes as the wavelength does as shown in Fig 2(b). Even though the measured RGB colours have fixed wavelengths, the H values converted from the RGB composition makes the same effect of change wavelength resulting from the colour change. Fig 2(c) ensures it by displaying the actual spectra obtained from pH colour changes. The colour change from pH 9 to 5 follows the direction of decreasing H, but does not the composition of RGB. Even though the wavelength and H do not have a straight linear proportionality, the polynomial fitting can be used to find correct values.[19, 28]

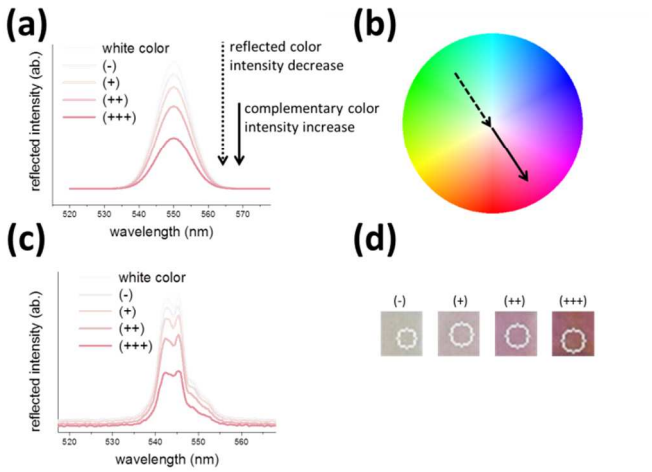

Fig. 3. (a) The displayed spectra are simulated to present only the G colour of which the wavelength is 550 nm. Simulation was conducted to gradually decrease the intensity of the spectrum by the increased concentration of the analyte. However, what is optically observed is the increasing intensity of the complementary colour because the sensed colour originates from the reflected light. (b) The colour space shows how the intensity decrease of a colour (dotted arrow) is related to the intensity increase of the complementary colour (solid arrow) in terms of S. (c) The spectra and (d) the optical images were measured on the bilirubin paper sensors at concentrations of 0, 0.5, 1.0 and 3.0 mg/100 mL corresponding to (-), (+), (++) and (+++), respectively.

The intensity change is characterized by the saturation (S) values as S changes monotonically with intensity.[16] However, in the colorimetric measurement, the observed colours are the result of the reflection of the incident light on the sensor paper, so that the increased intensity of a certain colour results from the decreased intensity of its complementary colour. Fig 3(a) illustrates the decrease of 550 nm expecting that the green colour turning paler as indicated by the dotted arrow in Fig 3(b). However, what is actually observed is the pink colour (complementary to green) turning more vivid as indicated by the solid arrow. Fig 3(c-d) show the actual spectra and the optical images obtained from the colour change by concentrations of bilirubin. Decrease of the spectrum intensity is measured as increase of the S value of the complementary colour.

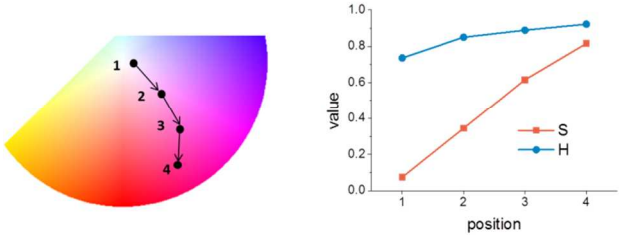

Fig. 4. A simulated colour change is shown at positions of 1 to 4 on the colour space and the colours are converted to the H and S values and plotted along the position.

In the real system, no measured colour change is presented by only H or S as shown by the perfect circle or the exact linear line in Fig 2 and 3. The co-play of H and S changes the colours so we need to choose whichever shows the better sensitivity

and clarity. In Fig 4, a colour change is simulated by changing both H and S, and the values are plotted along the position. The S value change is more distinguishable than the H value, which means that S is the better parameter to determine the concentration. Using this protocol, we determine the H- and S-types for each analyte in our urine test. The sensors belonging to the H type are ascorbic acids, specific gravity, pH, glucose, protein and RBC, and the sensors belonging to the S type are leucocytes, nitrite, ketones, urobilinogen, and bilirubin, respectively.

Using the reference colour chart that comes with the urine test strip, we made a set of new calibration curves. We took the reference colour chart with the test strip and evaluated all the colours using Eq (1). Then, the concentrations of each analyte are described as functions of either H or S of the colours corresponding to negative and positive Levels 1, 2 and 3. Detailed information is provided in the Electronic Supplementary Information (ESI). Then, the calibrated curves are loaded on the smartphone and ready to be used for diagnosis.

Experimental

Development of a smartphone app to operate the diagnosis.

A mobile software (so-called app) carrying out the above procedures was developed on the Android platform. The app was sophisticatedly coded by Java using ADT (android development tools)[29(a)] and functions of the smartphone were controlled through APIs (application programming interface). For easier programming, we employed OpenCV[29(b)] to handle processes of complex algorithms such as image rendering, histogram equalizing, threshold management and the template match.

Devices.

The smartphone was Samsung Galaxy Note 3 which has S800 CPU and 13 M pixel camera. Its high performance CPU enables the image recognition and the calculation in real-time and the highly resoluble camera produces finely digitized images. A commercial urine analyser, Uriscan Optima, purchased from YD-diagnostics, the same company of the urine strip, was used to compare the diagnosis results of the app. A spectrometer, MAYA 2000 pro purchased from Ocean Optics, was used to measure the spectra of the colorimetric sensors under the fluorescent light condition.

Materials.

Uriscan strips and Uritrol sets were purchased from YD-diagnostics. Uriscan strips are the paper-based multi-purpose urine test strip and Uritrol sets are standard urine samples consisting of highly concentrated ascorbic acid, leucocytes, glucose, nitrite, protein, ketones, bilirubin and red blood cells (RBC). The stock standard solutions were prepared by dissolving the samples in 10 mL doubly distilled water to have the concentrations equivalent to positive Level 3. The lower level solutions were prepared by diluting the stock solutions and the levels were confirmed by Uriscan Optima. For further quantitative analysis, L-ascorbic acid (99.5 %) and bilirubin (99.0 %) purchased from and Samchun Chemicals and Acros Organics were dissolved in the pH 6 buffer solutions to meet the concentrations of positive Levels 1, 2 and 3. The concentrations are 10, 25 and 50 mg/100 ml for L-ascorbic acid and 0.5, 1.0 and 3.0 mg/100 ml for bilirubin, respectively. Buffer solutions of pH 5, 6, 7, 8 and 9 were made from appropriate amounts of sodium citrate, citric acid, KH_2PO_4, K_2HPO_4, NaH_2PO_4, Na_2HPO_4, boric acid, and NaOH according to the procedures in the reference.[30]

Results and Discussion

Comparison of signals measured under different light sources and illuminance.

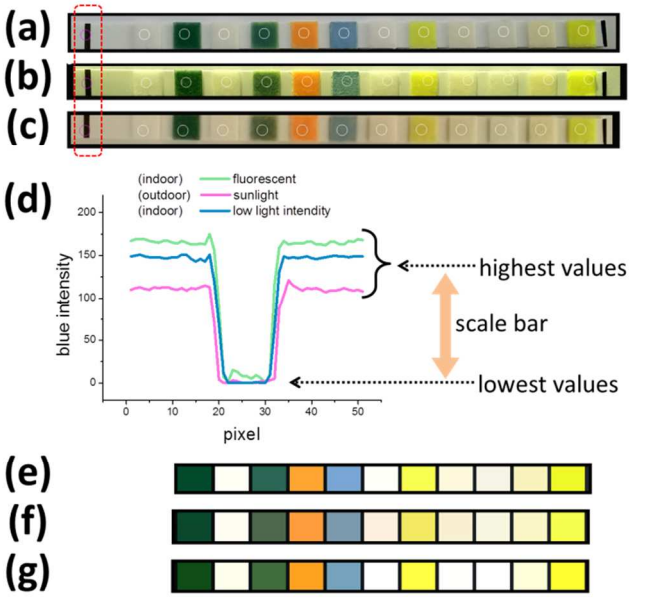

Fig. 5. Optical images of a urine strip prepared with the doubly distilled water were taken under (a) the indoor fluorescent, (b) the outdoor sunlight and (c) the indoor low light intensity conditions. (d) The blue colour profiles of the black and white background were measured in the dotted red rectangle in (a-c). (e-g) The corrected colours were obtained from the colours of (a-c) by the correction protocol.

In order to see the effect of the light sources on the image digitization and colour evaluation, we measured one sample under different conditions. The sample was prepared using the doubly distilled water to make it influenced only by the light being free from any effect of the analytes. Fig 5 shows the pictures taken under the conditions of (a) the indoor fluorescent light, (b) the outdoor sunlight and (c) the indoor low light intensity. As the colours look different in the picture, their digitized values are different depending on the light conditions. It means that the colour values of the digitized image cannot be

used as obtained to the pre-loaded calibration curves. In this report, we use the black and white background as the reference to compensate the differences and to obtain the balanced RGB colours. Fig 3(d) shows blue colour profiles out of the RGB over the black and white background region indicated by the red rectangle and the measured highest and lowest values are used as R_W and R_B in Eq 1. Based on the compensation protocol, we manage to find the corrected colours which will be transformed to the HSV colour space. Even though the raw colours taken from the same sample under different conditions look different each other, the corrected colours shown in Figure 3(e)-(g) look very similar. It was also confirmed with a normal urine sample. The concentrations of the analytes measured under the fluorescent light and the sunlight were calculated from their corrected colours upon the pre-load calibration curves and compared in the plot of Fig 6. Here, the concentrations are normalized to the individual concentrations of positive Level 1 of each analyte.

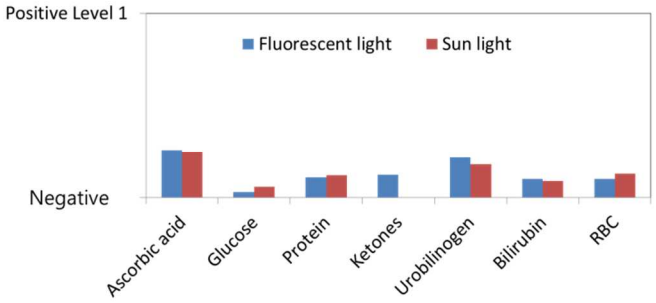

Fig. 6. Comparison of the concentrations contained in a normal urine sample measured under the fluorescent light and the sunlight, respectively. The concentrations are normalized by the concentrations of positive Level 1 of each analyte.

Quantitative analysis using the standard colour charts.

We developed an app which carries out conversion of the colour on the urine test strip to the concentrations of the analytes. In order to confirm its proper functionality, we first tested the app to the standard colour chart that comes with the urine test strip.

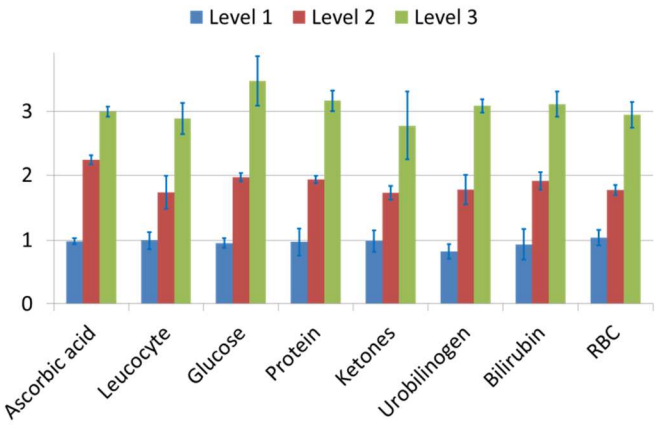

Fig. 7. The standard colours of positive Levels 1, 2 and 3 of each analyte were measured using the app under the indoor fluorescent light and the outside sunlight. The average values (n=6) and the standard deviations are plotted along the analytes.

Practically, the pre-loaded calibration curves in the app were made using the standard colour chart so that examination of the app with it should confirm the practical use of the app. The tests were done under the indoor fluorescent light and the outside sunlight and the results are shown in Fig 7. The y-axis represents the positive response levels of each analyte. For example, as to the ascorbic acid, Level 0 is the negative response and Levels 1, 2 and 3 are positive responses with concentrations of 10, 25 and 50 mg/100 mL, respectively. Information of the other analytes is tabulated in Table S1 in the electronic supplementary information. The result shows that most of the data are in a good agreement of our expectation within acceptable error ranges except some tricky analytes. This observation result should be reviewed in two analytical viewpoints; accuracy and precision. The measured values should be exactly the same as the concentration level on the y-axis to offer good accuracy but some are just close to the levels. This problem can be solved if we correct the pre-load calibration curves with actual colours and values measured through this app. Second, the precision can be represented in terms of standard deviation of the plot. Large deviations are shown at the high concentration levels of ketones and glucose and the low concentration levels of protein and leucocytes. The reason for it can be ascribed to the limitation by the low resolution for distinguishing similar colours in the ambient conditions. While usual spectroscopy experiments are done in the well-controlled light conditions, our snapshot measurement is not because our method is designed to be versatiley used at anyplace for POC tests. Due to the low resolving power, some colours are hard to tell from another. Another reason is that only one colour coordinate (H or S out of HSV) is used to calculate the concentration while a colour is fully described by three coordinates of either RGB of HSV. For example, the calibration curve for the ketones is made by the S values on HSV. The colour of Level 2 is almost saturated and very close to the colour of Level 3 in terms of S while they are different in terms of H, which differentiate those two colours. This problem can be solved if we make a delicate calibration curve using a complex algorithm for the combination of S and H. All these results prove our concept of using a smartphone as a stand-alone colorimetric device without auxiliary accessories and trained skills, which has high potential of the point-of-care analysis for everybody, especially patients and old people away from hospitals and laboratories.

Diagnosis with the standard urine sample.

To further prove the real applicability, we conducted diagnosis using the app with standard urine samples and compared the results from the app to a commercial urine strip analyser. After the process of taking a snapshot as shown in Fig 1, the app immediately shows the diagnosis results.

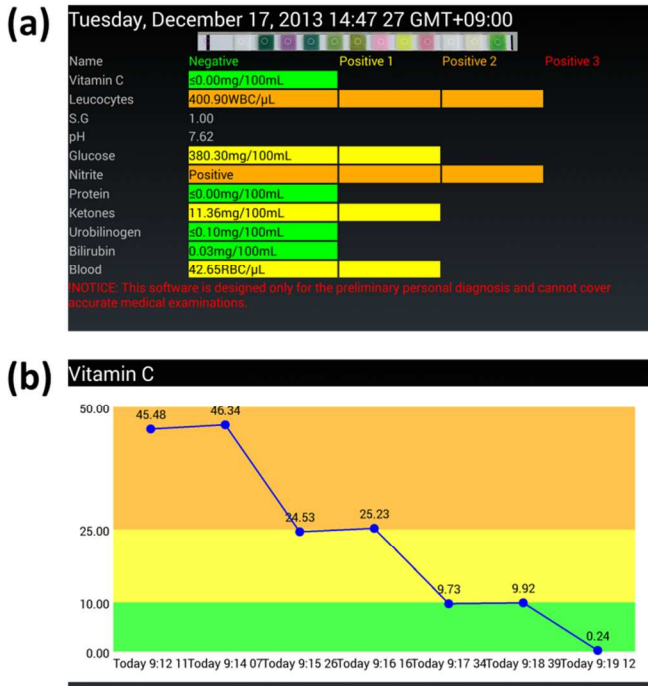

Fig. 8. Screenshots of the app showing (a) the results of a sample solution containing leucocytes, glucose, nitrite, ketones and RBC and (b) the history of the past results to help users to track their health status. This screen was capture after 0, 10, 25 and 50 mg/100 ml of ascorbic acid (Vitamin C) solutions were measured

Fig 8 shows the actual screenshot of the app measuring a sample diluted from Uritrol 2 standard solution which contains high concentrations of leucocytes, glucose, nitrite, ketones and RBC. The top picture shows the captured image (before the colour correction) and the circles indicate the areas where the colours are acquired. Diagnosis results are displayed visually by the length and the colour of the bars beside the name of the analyte with concentrations. The length elongates and the colour changes from green to red by the degree of danger. The other analytes examined using Uritrol 1 and 3 except urobilinogen (not present in the provided urine samples). With varying the concentrations of the standard Uritrol 1, 2 and 3 solutions, we measured the urine samples by the app and a commercial analyser (Uriscan Optima). The diagnosis results are compared and summarized in Table 1; O is marked to the results matching each other over 90 % and Δ to 70 ~ 90 %. Here the low matching percentage is ascribed to the ambiguous determination at the border between the adjacent levels. For example, when the measured concentration of ascorbic acid is 17 mg/100 ml, its response can be categorized in either level 1 or level 2 depending on the error that we discussed about in the previous section. Considering such uncertainty, the results in Table 1 are acceptable to prove the real applicability of our analytical method.

Table 1. Comparison of the diagnosis results made by the app and a commercial urine analyser.

Analyte \ Response	Negative	Positive		
		Level 1	Level 2	Level 3
Ascorbic acid	O	O	O	O
Leucocyte	O	▲	▲	O
Glucose	O	O	▲	▲
Nitrite	O	O		
Protein	O	▲	O	O
Ketones	O	O	▲	n/a
Urobilinogen	O	n/a	n/a	n/a
Bilirubin	O	O	O	O
RBC	O	O	O	O

The results are summarized according to the matching percentage.
O: 100 ~ 90 % and ▲: 90 ~ 70 %. The full data can be found in the ESI.

Once the diagnosis is done, the results can be saved and recalled whenever it is needed. It can also show the history of the recent results so that users can track their health status. To clearly demonstrate it, we prepared standard solutions of ascorbic acid of which the concentrations were 0, 10, 25 and 50 mg/100 ml and measured them successively. Fig 8(b) is a screenshot of the app showing the last 7 results along the measured time.

Conclusion

The paper-based colorimetry has been emerging in the field of the point-of-care system as it provides a portable, inexpensive and convenient analytical technique. While its medical or environmental diagnosis is usually conducted by reading the colour changes through naked eyes or specifically designed device, recently it is assisted by smartphones in converting the colour changes to digitized values for more accurate and versatile measurements. This report evolves the concept of the smartphone-based colorimetry to the multi-analyte detection. Once the snapshot of the paper-based sensor array is taken through a smartphone, the smartphone finds the colour sensors and calculates the concentrations of the analytes from the colours based on the procedures that we have proposed. Here two technical significances are implied. One is that multi-target analysis on an array can be done swiftly by the automatic recognition. Considering the 1000 wireless sensing electrodes in a large scale array activated in a 2D electric field,[31] our technique can be applied to address each electrode to obtain the specific spot information. The other is that the self colour-correction enables the pre-loaded calibration curves to be readily applied regardless of the light conditions. It removes additional hardwares and measurement requirements for

calibration. To realize our proposal, we programmed a smartphone app for the POC urine diagnosis and tested it with standard urine samples to confirm that it properly worked in the real system. As the app only requires a paper-based sensor, it is presumed to offer the best smartphone-based colorimetric method suitable to the ideal POC diagnosis.

The smartphone technology develops dramatically with taking in more sensing units. Not only for vision, sound and global positioning, sensing units for temperature, pressure, humidity and even radiation are already embedded in a small smartphone. As the built-in camera is utilized as the transducer combined with bio-chemical sensors, other units can be utilized to more diverse medical and environmental POC applications. Our group will report more smartphone-based analysis research and release related smartphone apps[32] on due course.

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Notes and references

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Electronic Supplementary Information (ESI) available: The tables of (1) the concentrations of each analyte ascribed to the positive Levels 1, 2 and 3, and (2) the matching percentage of the diagnosis results obtained by a commercial analyser and the smartphone app are provided. See DOI: 10.1039/b000000x/

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Development of the Smartphone-based Colorimetry for Multi-analyte Sensing Arrays

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Here we describe the smartphone-based colorimetry to quantify multiple analytes by employing the automatic recognition and the self color-correction.