



Article

An IoT-Based Automatic and Continuous Urine Measurement System

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Abstract: Urine output is an important indicator of renal function. In hospitals, urine is collected using a catheter connected to a urine collection bag that has volume gradation markings. This type of visual measurement has low levels of accuracy and is labor-intensive. This paper developed an Internet-of-Things enabled system that continuously monitors the urine volume collected via the urine collection system. The device is built utilizing a strain gauge load cell, an integrated circuit that contains an amplifier, analog-to-digital converter, and a WiFi-enabled microcontroller. The data is sent via wireless networking to a data collection and analysis server, which provides accurate analyses of urine output. A mobile application utilizing the Blynk.io system is used to display the data. This device and mobile application were built at a minimal cost of 26 USD. The device has been tested multiple times and reported urine output accurately, with minimal difference between actual versus measured volumes. In the future, further development of this device can provide hospitals and physicians worldwide with easy access to affordable, accurate, and real-time urine measurement, which would translate into better, life-saving medical care.

Keywords: foley catheter; urine catheter; vital signs; monitoring; urine collection system; urine output; renal failure; renal impairment; urinary impairment

**Citation:** Lee, A.; Lee, M.; Yeh, H.-J.J.An IoT-Based Automatic and Continuous Urine Measurement System. *BioMedInformatics* **2023**, *3*, 446–454. <https://doi.org/10.3390/biomedinformatics3020030>

Academic Editor: Hans Binder

Received: 14 April 2023

Revised: 21 May 2023

Accepted: 31 May 2023

Published: 5 June 2023



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1. Introduction

In a hospital or healthcare facility, urine is collected and analyzed to evaluate kidney function. Accurately measuring urine output in hospitalized patients is critical in the treatment of patients with acute renal injury, sepsis, and other medical conditions [1]. Most urine measurements are done by nurses who manually examine the gradation markings on the urine collection bag to approximate the amount of urine collected. The Foley catheter is inserted through a patient's urethra into the bladder, which collects urine into a bag, which is then quantified visually and calculated as urine output over a period of hours (mL/h) [2]. Manual measurements are laborious for the nursing staff, and this is one reason why it is usually not done frequently. Furthermore, studies have shown that electronic measurement of urine output is more accurate than manual measurements [3]. However, such electronic devices are extremely expensive, so their uses are currently very limited.

One type of electronic device currently on the market to measure urine output is the RenalSense Clarity RMS Sensor Kit [4]. The device involves the use of patented sensors and costs about 5000 USD for the console, and 85 USD for each single-use specialized temperature-sensing urine collection bag [5]. The technology is based on the principle of thermal transfer. The literature available does not elaborate further on the specifics of this technology. This equipment is cost-prohibitive for most hospitals, resulting in few hospitals using this device.

Sensica Urine Output System [6] is another commercially available continuous urine monitoring device, but it was recalled in 2022 due to inaccuracies [7]. A thorough literature search did not yield information on what engineering principles the device was based on or how the device was developed. There are several other devices that are commercially available, such as the Accuryn Monitoring System [8], but the companies do not disclose the technology used in the development or the accuracy of the devices. Furthermore, most of them are approved only in certain countries, such as Israel, and not in the USA.

There have been other urine output measurement systems proposed, but they were not commercially developed due to various reasons. One such proposal was by Otero et al. That device used capacitive sensors in the form of floating rods for measuring the amount of urine within a rigid container. The rods would move depending on how much fluid was in the container. The rods' relative position in the container would be an indicator of how much urine was collected. The device required a significant amount of space and time to set up [9]. Likely due to these limitations, the device was not commercially developed.

This paper provides a new device for automatic urine output measurements. The primary feature of this device is to eliminate the need to take urine volume measurements manually by visual inspection. It reduces the labor and cost of the process by automatically and constantly measuring the weight and hence the volume of the urine. The collected data is sent wirelessly to a server and directly to mobile devices accessible to doctors and other healthcare providers. This device is designed to have a very low cost compared to other available automated urine measurement systems. The device provides highly accurate and frequent readings that far exceed what is available with manual measurements (i.e., visual inspections).

The enhanced frequency and accuracy of this device are expected to provide additional data to the healthcare provider that can have greater therapeutic value and lead to better health outcomes. This device may have applications in healthcare areas where fluids are collected and can be measured cheaply and accurately. These additional uses are under investigation.

This device, referred to as the Internet-of-Things (IoT) Urine Scale, was developed at a minimal cost of 26 USD and was built using a strain gauge load cell, an integrated circuit that contained an amplifier, analog-to-digital converter, and a WiFi-enabled microcontroller. The data was sent via wireless networking to a data collection and analysis server, which provided accurate analyses of urine output. A mobile application utilizing the Blynk.io system was used to display the data (Figure 1). This device was built specifically to measure urine output in a hospital setting. For this device to measure other types of fluid collection, additional computer programming would be required to incorporate the different fluid densities required to convert the fluid weight into volume.



Figure 1. Diagram of the flow of information from urine collection device to IoT Scale to Blynk cloud to cell phone.

The device was able to measure as frequently as in 1 s intervals the volume of urine collected with a high level of accuracy. The commercially available RenalSense Clarity RMS Sensor Kit measures urine output every 15 min, and the Sensica Urine Output System measures urine output in 1 min intervals. There are currently no commercially available devices that measure urine output in the 1 s interval range.

2. Materials

The monitoring system in this new device consisted of the following elements:

- (1) IoT sensor nodes on which the urine collection bag was hung
- (2) Weight sensor that measured the urine weight
- (3) Internet-capable processing device that collected, interpreted, and transmitted the sensor data
- (4) A secure, wireless network such as WI-FI
- (5) A data processing server that controlled and received urine bag collection data
- (6) A program on the server that performed an analysis of the urine output data
- (7) A user interface, such as a mobile application, that displayed the urine output graph and results

3. Methods

For the initial system, a commercially available electronic hanging scale for the mechanical housing and weight sensor was chosen [10] (Figure 2). These scales are commonly available for the measurement of fish weight for sports fishing and luggage weight for traveling. A strain gauge is typically used as the weight sensor in the hanging scales. These sensors respond to applied force (weight) by elastic strain (deformation) on a rigid metal beam or member, which produces a change in the electrical resistance of a material deposited on the beam or strain gauge [11]. The hanging scale provided weight ranges of approximately 0–10 kg at 5 g resolution and 10–50 kg at 10 g resolution. These values indicated the capabilities of the strain gauge. They exceeded the typical urine collection bag weight range required and provided approximately 5–10 mL of resolution. The scale was compact, measuring 94 mm (h) × 51 mm (w), and lightweight (159 g). A hook measuring 6.1 mm (h) × 24 mm (w) was attached to the scale. This hook allowed the urine collection bag to be attached.



Figure 2. Photograph of the initial electronic hanging scale (on left) [10] connected to the HX711 amplifier and ADC module (center) [12] connected to the M5Stick IoT CPU + WiFi device (on right) [13].

The strain gauge was connected to a semiconductor device, which measured and amplified the change in resistance. The semiconductor device also converted the analog measurements into a digital form that could be displayed on a mobile application. The semiconductor device used was the HX711 integrated circuit produced by Avia Semiconductor [12] (Figure 2). The HX711 also contained the amplifier and analog-to-digital converter (ADC). These modules are commercially available and are typically used for bathroom scales. The HX711 featured a relatively fine analog resolution of 24 bits at a relatively slow measurement speed of 10 or 80 Hz.

The HX711 was then connected to a microcontroller. The microcontroller was able to collect the data and transmit that information wirelessly via the internet. The Espressif Systems ESP32 microcontroller [14] was chosen because it provided WiFi connectivity and had good computing performance at low power. It was also compatible with the Arduino Integrated Development Environment (IDE) [15]. Of the many available modules containing the ESP32, the M5StickC device [13] (Figure 2) was chosen because it was small ($48.2 \times 25.5 \times 13.7$ mm), lightweight (15 g), and had a robust package. The M5 StickC device fitted inside the hanging scale housing and had an integrated 120 mAh battery and charger. The IoT device operated with the concept of “virtual pins”, which were essentially data channels that allowed bidirectional communications from the IoT hardware to the server and from the server to the mobile device.

For the software, the system Blynk.io [16] cloud-based IoT platform was used. The Blynk system provided libraries for the Arduino IDE and applications that ran on iOS, Android mobile phones, and Web browsers. Arduino IDE provided a simple programming environment in C++ with many open-source libraries.

From the mobile application, activating a software button initialized the IoT Urine Scale. The IoT Urine Scale device measured and stored the tare weight of the urine collection container. The M5StickC continuously measured the weight of the urine collection bag and sent the data to the Blynk server at 1 s intervals. Other data, such as the battery condition of the M5StickC, was also sent to the Blynk server. The urine weight was converted to urine volume by the device, and that information was displayed as numerical values and graphs on the mobile phone.

4. Results

The IoT Urine Scale was assembled (Figure 3), and the urine collection system was hung onto the scale as an experimental setup (Figure 4). The system was calibrated using a known weight by setting the scaling factor to the net weight value divided by the HX711 ADC reading at the weight. The weight of the device and urine collection bag changed the loading force on the strain gauge. The IoT Urine Scale and urine collection bag needed to be tared before measurement could begin. After being tared, the device could start to measure the weight of the water (to simulate urine) being collected. This measurement data was then sent to the Blynk cloud server via WiFi. Graphs from the IoT Urine Scale were then displayed on iOS smartphones and Web pages. One trial tested the injection of 20 mL of water over 30 s into the urine collection bag. That data was correctly displayed on an iOS smartphone (iPhone 14) (Figure 5).

In the metric system, the mass of 1 gm of water is equivalent to a volume of 1 mL at 40 °C. For temperatures up to 100 °C, the mass and volume of water vary very little [17]. The specific gravity of urine is 1.002 to 1.030 [18], which is very similar to that of water, which is 1. For the development of this device, we can assume that urine also has a specific gravity of 1, like water. Since urine measurements are done at ambient room temperatures, well below 100 °C, we can further assume that for both urine and water, mass and volume are equivalent. One gram of measured urine can be converted to 1 mL of urine by our device. One gram of urine is equivalent to 1 mL of urine with only a 0.5 to 3 percent error. For ease of understanding, in the rest of this paper, we will be using the terms “mass” and “weight” interchangeably when referring to water or urine.



Figure 3. Photograph of the assembled IoT Urine Scale.



Figure 4. Photograph of the experimental setup.

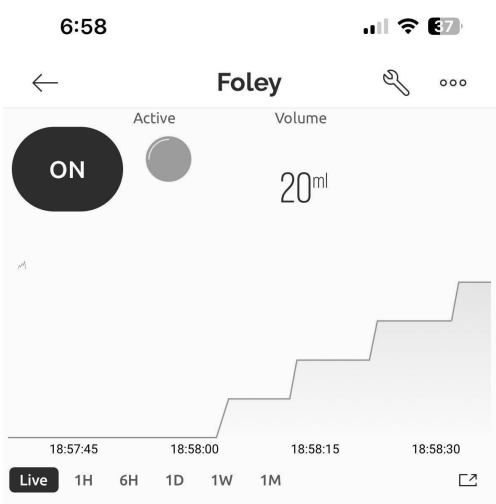


Figure 5. Screenshot of urine monitoring application as seen on a mobile phone.

The device was tested for accuracy by measuring how well the measured volumes correlated to actual volumes of urine output. In our trials, water was used to simulate urine. Water was injected into the tubing of the urine collection bag. In each trial, water was injected every 2 min in increments of 250 mL for a total of 2000 mL over a period of 14 min. The maximum volume of 2000 mL was chosen because that was the capacity of standard urine collection bags. Since the testing showed very little variation in results each time, the testing was ended after 20 trials. The results from each of the 20 trials were then averaged, with the known volumes versus the measured volumes by the IoT Urine Scale compared (Figure 6). The measured volumes correlated directly with the known volumes, with a mean difference of 66.1 mL (median 60, SD 39.3, 95% CI 11.6). At 250 mL of water, the average measured volume was 10 mL greater than actual volume. At 2000 mL, the measured volume was 100 mL greater than actual volume. The device measured urine output trended directly with actual urine output.

In order to troubleshoot the cause for the difference between measured and actual volumes, both the software/programming code as well as the hardware components individually were re-examined. After much trial and error, the most likely cause for the difference was deduced to be errors in the calibration constant of the programming code. This calibration constant was repeatedly re-calibrated, and more trials were done. After re-calibrating the calibration constant, another 20 trials were repeated, identical to the first set of trials. This time, the measured urine output correlated much more, although there was still a mean difference of 16.3 mL (median 12.5, SD 17.3, 95% CI 11.2 to 21.4) (Figure 6) between the measured versus actual volumes.

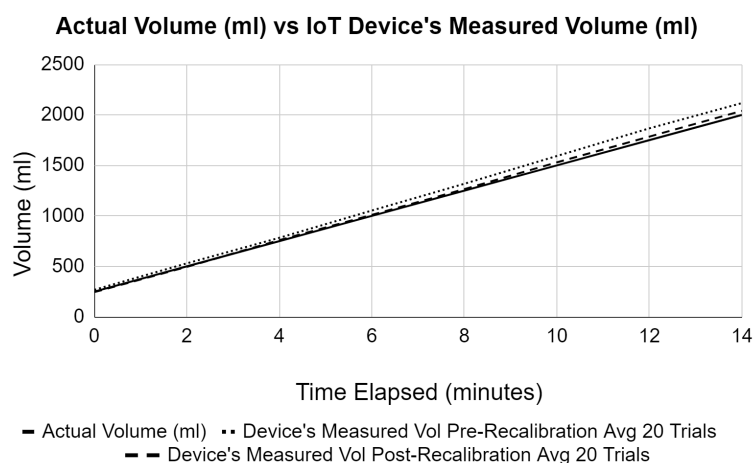


Figure 6. Urine Output Trials of IoT Urine Scale (device) using water to simulate urine.

Lastly, another set of 20 trials measuring the IoT Urine Scale's accuracy at 97 mL was conducted in order to compare the IoT Urine Scale's accuracy to a study done by Goldman et al. Water (to simulate urine) was again used in these trials. At 97 mL, the IoT Urine Scale had a mean difference of 0.8 mL (median 1.0, SD 1.2, 95% CI 0.67 to 0.93) between the actual versus measured volumes of urine.

5. Discussion and Conclusions

The developed IoT Urine Scale has been very successful in capturing simulated urine output. There was a 16.3 mL mean difference (median 12.5, SD 17.3, 95% CI 11.2 to 21.4) between the IoT Urine Scale measurement to the actual volume in measuring volumes ranging from 0 to 2000 mL. The IoT Urine Scale is still more accurate than the manual measurement of urine output. In clinical medicine, this percentage error is negligible and will not affect patient treatment and outcome. The IoT Urine Scale measurement results were also analyzed and compared to the most common measurement technique used today, which is manual measurements done by nurses visually looking at the urine bag gradations. In a study conducted by Goldman et al., the measurements done by the

nurses had a mean difference from the actual volume of 8.5 mL (SD 46.091, 95% CI 5.4 to 11.7). The nursing measurement had a significantly large standard deviation of 46.091 mL. In that same study, the mean difference from the commercially available RenalSense Clarity RMS Sensor Kit to the actual volume was -2.55 mL (SD 25.771, 95% CI -4.3 to -0.8). Although the mean difference was smaller, the RenalSense Clarity RMS Sensor Kit still had a notably large standard deviation of 25.771 mL. The mean urine volume measured in Golman et al.'s study was 97 mL. Our IoT Urine scale, when tested 20 times at 97 mL, had a difference of 0.8 mL (median 1.0, SD 1.2, 95% CI 0.7 to 0.9) between the actual versus measured volumes. The mean volume difference and standard deviation for our device were significantly smaller than the RenalSense Clarity RMS Sensor Kit and the nursing measurements. There are other electronic urine output measuring devices, such as the Accuryn Monitoring System and Sensica Urine Output System; however, there are no published studies evaluating the accuracy of these devices. It should be noted that the Sensica Urine Output System was recalled by the US Food and Drug Administration in 2022 due to its inaccuracies [7]. At the time of recall, there were 457 units in use. This also shows that very few of these electronic urine measurement devices were being used in hospitals.

The IoT Urine Scale developed by us is able to measure fluid volume collection over a wide-ranging frequency of time, from seconds to hours, depending on the user's preference, and transmits the data directly to the physician or other healthcare provider. This technology bypasses the labor-intensive, inaccurate, and infrequent measurements made by the nurse, which may be done only two to three times a day. Infrequent monitoring may be disadvantageous to a patient's health. For instance, in specific hospital settings, especially the intensive care unit or operating room, careful and frequent urine output monitoring can be extremely important. For patients with heart failure, urine output is an essential measurement because the physician reviews that data to determine if adequate amounts of fluid have been removed from the patient and if medication needs to be adjusted. In one study, researchers found that minute-to-minute changes in urine output can provide earlier detection of life-threatening conditions, such as sepsis [19]. It would be very beneficial to have real-time, continuous measurement of the urine output in minutes (mL/min) or even in seconds (mL/s), compared to the current standard of hours (mL/h), to improve the health outcome of patients. Our device is able to provide measurements in a smaller time interval of 1 s compared to the electronic devices in the market, which, at best, measure at 1 min time intervals [4].

The change in the rate of urine output (Δ mL/min) has previously not been mentioned in medical journals because it is too difficult for the nursing staff to monitor the urine output at short intervals, such as in minutes or seconds. The urine bag and gradation markings inherently make urine volume measurement inaccurate. As a result, the change in the rate of urine output cannot be accurately calculated. In hospitals and nursing homes, the urine output is usually manually measured once every 1 to 24 h, with 1 h usually reserved for the most critically ill patients, as it is very labor intensive. Since this IoT Urine Scale is able to measure the urine volume change over 1 s, an accurate change in urine output rate (Δ mL/sec) can also be calculated. A change in urine rate can allow for the monitoring of subtle changes in kidney function, which will alert the clinician to the possible onset of acute renal injury or renal failure much sooner and thus implement life-saving measures quickly.

The integrated battery in the M5StickC is small (120 mAh), and the run time is low at approximately 1 h per charge using the current firmware. Significantly longer run-time can be achieved by taking readings at longer intervals and putting the M5StickC device to low-power consumption sleep mode while not actively taking a reading. For example, the estimated run time using a 5 min reading interval can improve the run time to more than 10 h while still being able to provide a good urine output rate in mL/h. An external battery pack can also be connected via USB to the M5StickC through a port on the hanging scale housing, or a larger integrated battery such as the 18650C HAT [20] module that provides 2200 mAh of power for 19 times the run time. The size of the battery module is

150 mm × 24 mm × 24 mm, and the weight is 90 g, which will require a larger housing. This would result in a run time of 19 h to at least 190 h using a 5 min reading interval. If an electrical outlet is nearby, which is usually the case in most clinical settings, the IoT Urine Scale can be adapted to plug into it via USB, just as with other medical equipment. The battery life would not be an issue in this case, and the IoT device could run indefinitely.

We propose the difference in the actual versus the measured volume of the simulated urine is due to the accuracy of the calibration constant. Re-calibrating this constant helped tremendously, and the measured volume became much more accurate. With production devices, it is expected that each device is to be calibrated individually during production to accurately set the calibration constant. Another possibility for the percentage error may be the fluctuation in the ambient temperature, which may affect the hardware in the device. Future work can be done on refining the accuracy of urine measurements. This IoT Urine Scale thus far has been shown to be much more accurate than manual measurements and even with commercially available electronic measurement devices.

Future experimentation on this device can include testing the device's accuracy over a 24 h period. This would more precisely simulate the time frame urine output would be monitored in hospitalized patients. In hospital settings, different patient rooms in the hospital may have different temperatures. The device can also be tested for accuracy at these slightly different room temperatures.

In summary, the developed IoT Urine Scale is of a very low cost (26 USD), compatible with current standard urine collection bags, and highly accurate. Due to the device's affordability and adaptability, and ability to provide real-time urine output to a doctor remotely, we feel this device has the potential to be adopted by hospitals around the world to improve patient care and save lives.

Author Contributions: Conceptualization, A.L.; methodology, A.L.; software, H.-J.J.Y.; validation, M.L.; formal analysis, A.L. and M.L.; investigation, A.L. and M.L.; resources, H.-J.J.Y.; data curation, A.L., M.L. and H.-J.J.Y.; writing—original draft preparation, A.L., M.L. and H.-J.J.Y.; writing—review and editing, A.L., M.L. and H.-J.J.Y.; visualization, A.L.; supervision, H.-J.J.Y.; project administration, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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