Inaccuracy of Urine Output Measurements due to Urinary Retention in Catheterized Patients in the Burn ICU

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Electronic urinary output monitors, intended to provide urine output information to guide fluid therapy during burn resuscitation, can be inaccurate because of airlocks causing urine retention in the drainage tube and bladder. In this study, the authors explore the effects of airlock formation on urine output measured using an electronic urinary output monitor connected to either a standard commercial drainage tubing system or a drainage tubing system with an automated airlock clearing mechanism. In a multicenter study in the burn intensive care unit, urine output was compared between 10 control patients with a standard commercial drainage tubing system and 10 test patients with a novel automated airlock clearing drainage tubing system. The comparison was focused on identifying the number and magnitude of surges in urinary output because of airlocks and associated periods of false oliguria. In the control group, 5 of 10 (50%) patients had drainage line flow impediments from 8 airlocks. In addition, control patients experienced six associated periods of false oliguria. Airlock surge volumes ranged from 50 to 329 ml, and false oliguria duration ranged from 39.4 to 185.2 minutes. In the test group, 0 of 10 (0%) patients had drainage line impediments from airlocks ($P < .01$), and hence, there were no periods of false oliguria. Airlocks and associated periods of false oliguria occur with standard commercial drainage tubing and are eliminated using an automated airlock clearing drainage tube. Electronic urinary output monitoring with self-clearing drainage has the potential to improve tracking of real-time urine output and decrease caregiver workload. (J Burn Care Res 2017;38:e409–e417)

The rate of urinary output (UO) is the primary physiological sign guiding fluid therapy during burn resuscitation. Bedside caregivers use UO along with other indices of organ perfusion to titrate the fluid requirement for adequate cardiovascular function while avoiding fluid overload. Some of the morbidities attributed to overresuscitation, often termed "Fluid Creep," include pulmonary edema, paralytic ileus, and abdominal compartment syndrome.

It is the burn caregiver's challenge to observe the relationship between UO flow rate and infusion rate and to determine what infusion rate will be appropriate for the next hour. Inaccuracies in UO make this task more difficult. Unfortunately, standard methods for measuring UO are often inaccurate because of time measurement error and urine retention in the drainage tube and bladder. Urine produced during 1 hour may not be measured until later hours, creating or masking trends.

Burn unit standard operating procedure is that UO is measured every hour on the hour. However, more practically, UO is most often not measured precisely on the hour, as a busy nurse's priorities and available time often do not lend themselves to an exact on the hour task. A 5-minute error is introduced if one

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The study was a sponsor-initiated study supported by Theranova, LLC and the National Institutes of Health grants R44GM108320 and R43GM108320.

G.C.K. is a Chief Science Officer of Arcos, Inc. and CSO of Resuscitation Solutions, Inc. and hold equity positions; E.L., D.R.B., and D.N. are employees of Theranova, LLC and consultants to Potrero Medical, Inc.; and J.W. and B.C.F. have no competing interests to declare.

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1559-047X/2016

DOI: 10.1097/BCR.0000000000000405

measurement is just 2 minutes early, and the subsequent hour, the measurement is 3 minutes late, which is a common event. A 5-minute error of a 60-minute hour translates to a flow rate observation error of 8%. We found in an earlier study that the mean time error in routine intensive care unit (ICU) monitoring was 16 ± 15%.[1] Electronic urinary output monitors (eUOMs) can be set to measure precisely on the hour, which removes the timing error. However, the need to milk the drainage tubing can cause even larger errors particularly if the drainage tube is milked after an on the hour eUOM measurement.

Even when timing errors are removed, substantial errors can result from the urine retained in the tubing that connects the urinary bladder catheter to the urinometer. The internal volume of the standard drainage tubing is around 70 ml, which is almost twice a typical hourly UO of 30 to 50 ml. Further error can be generated because of retention of urine in the bladder trapped by a back pressure generated by urine in a dependent loop and its trapped air or "airlock."[2] If the nurse "milks" the drainage tube multiple times before a manual UO measurement, most of the urine retained in the tubing and bladder can be drained. But this process is inconsistently applied, time consuming, and often incomplete. Every milking of the drainage tube because of the nurse or patient movements causes a rapid surge in urine flow and volume, which is a measure of how much urine was cleared from the drainage tube and bladder. Milking is often followed by a period of no UO or false anuria as the tubing refills.

In this study, we focused on the extent of preventable urinary retention in both the tubing and the bladder by comparing the number and magnitude of UO surges and accompanying periods of oliguria that occur with and without the use of a novel antiairlock drainage tube. We used an eUOM in two groups of patients. One group used standard commercial drainage tubing, whereas the other group used a novel investigational drainage tubing system with automated airlock clearing every 5 minutes.

METHODS

Patient Population

Data reported in this study were collected from patients at the University of Texas Medical Branch, Blocker Burn Unit, Galveston, Texas, and the Joseph M. Still Burn Center at Doctors Hospital, Augusta, Georgia. Entry criteria included patients after their resuscitation phase with indwelling urinary bladder catheters and an expected placement of at least 24 hours. However, the policy of our institutions is to remove the Foley urinary catheter (Bard Medical, Covington, GA) as soon as it is not needed, so catheters were removed per policy and not influenced by the study protocol. Each patient included in the study was randomly assigned to either the test group (automated airlock clearing drainage tubing) or the control group (standard manually cleared drainage tubing). Exclusion criteria were patients younger than 18 years, diagnosis of end-stage renal disease, acute kidney injury (AKI) requiring renal replacement therapy, bladder or urethral trauma, or urinary tract infection (UTI) at the time of admission to the study. Patients provided their assent or consent to participate, and the protocol was approved by the Western Institutional Review Board and University of Texas Medical Branch's Institutional Review Board. Typical nurse to patient ratio at each site ranged from 1:1 to 1:2, and standard urine output monitoring for clinical care involved hourly electronic recording of urine output after drainage tube manipulation ("milking").

Device Description

In both the test and control groups, Criticore electronic urine monitors (Bard Medical) measured the UO volumes from patients with a standard Foley urinary catheter (Bard Medical). The UO was recorded through the serial port on the device. In the control group, the Foley catheter and the Criticore monitor were connected by a standard drainage tube (Bard Medical). In the test group, an investigational antiairlock device called Accuryn (Potrero Medical, San Francisco, CA) was placed between the urinary catheter and the eUOM (Figure 1). It was composed of two components: the sterilized and disposable antiairlock drainage tube and the reusable controller. The distal (patient) end of the Accuryn drainage tube was connected to a standard Foley bladder catheter and contained hydrophobic vents to prevent negative pressure from forming in the drainage tube and bladder. At the proximal end, a section of the drainage tube was placed into the controller, which then fed into the eUOM. The controller contained a cartridge designed to capture urine for real-time analysis, which increased the potential volume between the urine drain tube and eUOM, but did not impede drainage. To prevent the formation of airlocks, the controller utilized two peristaltic rollers driven by motors to clear the drainage tube of urine every 5 minutes.

Study Design

A total of 18 patients were enrolled. One patient in each group participated in the study twice (within the same group) with two periods of monitoring

Figure 1. Accuryn antiairlock system. The drainage tube at distal end (1) connects to a standard urine catheter. The Accuryn drainage tube proximal end (2) is placed in the Accuryn controller (3), which feeds into an electronic urinary output monitor (4).

separated by more than 2 days apart. Thus, there are performance data from 10 devices in the test group and 10 in the control group. In both groups, the Foley bladder catheter was inserted per the Instructions for Use. The volume of urine in the urine monitor was recorded every second. Both the control and test groups had manipulation or milking of the drainage line per standard unit policy, which typically occurred before the hourly recording of UO for the clinical use and electronic medical record entry. The Criticore Monitor was placed at the foot of the bed, per the Instructions for Use, to minimize dependent loop formation. Test and control patients were administered fluids and furosemide of varying dosage (20–100mg) intravenously and orally based on clinical need, per the standard of care at each center. In addition, the "maximum tubing retention volume," defined as the maximum amount of urine that could be contained within the drainage line in a clinical setting, was determined for test and control devices.

Data Analysis

Maximum Tubing Retention Volume. The maximum tubing retention volume represents the maximum amount of urine that can be contained within the drainage line in a clinical setting (Figure 2). This value is less than the total internal volume of the drainage tube. To determine the maximum tubing retention volume, the control and test drainage tubes were placed to mimic the set up in the clinic. A 16-Fr Foley was inserted through a 1/2" hole at the base of the side wall of an empty 500-ml plastic container, and a watertight seal was formed around the catheter (representative of the catheter being placed in the bladder). The drainage tube was placed in a configuration to provide the largest possible dependent loop to maximize tubing retention volume. The proximal end of the Foley catheter was secured to the table top in a horizontal position at a height of 30", representing the lowest setting on the typical hospital bed and worst-case scenario for the maximum tubing retention volume. The collection devices were placed on the floor with their midline 18" away from the anchor point of the Foley catheter representative of a device placed at the side of the bed versus the head of the bed, again representing the worst-case scenario for maximum tubing retention volume. The drainage tubes for each device were then attached to the Foley catheter at one end and the water collection chamber at the other end.

The 500-ml container was then filled with water and the water was allowed to flow through the system. If an airlock formed, the container was elevated to increase the pressure until flow resumed. At the first appearance of water in the collection chamber, the Foley catheter was clamped, and the water remaining in the drainage tube and Foley catheter was emptied into a graduated cylinder and the volume was recorded. The experiment was run in triplicate for each system yielding a mean tubing retention volume of 40.8 ± 0.74 ml for the control device and 32.2 ± 0.74 ml for the test device.

Airlock Analysis. Data were analyzed by converting the recorded 1 Hz volumes into flow rates at 30-second intervals and detecting airlock events based on the acute surge in urine output from the bladder that occurs when an airlock is cleared, typically through manipulation of the drainage line by medical staff. Acute surges used to identify airlocks had three characteristics: 1) a high flow rate that occurs with sudden emptying of retained urine, 2) a surge period bounded by a low flow rate to eliminate the longer lasting surges because of active diuresis that also would have met the high flow rate, and 3) a surge volume greater than the maximum tubing retention volume for either test or control devices, which would indicate that urine was retained in the bladder because of the airlock event.

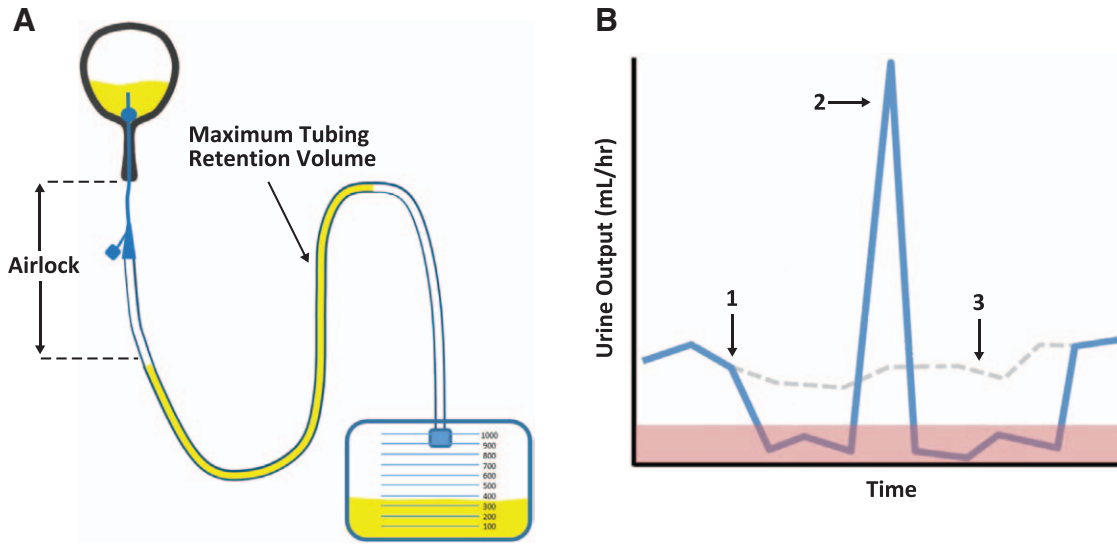

Figure 2. A. Airlock formation in urine drainage line with urine retained in bladder. B. Characteristics in urine output because of airlocks and break in airlocks observed through data analysis. *1*, airlock formation; *2*, acute surge after break of airlock; *3*, true urine production without airlocks.

High Flow Rate. Acute surges used to identify airlocks required a minimum flow rate, measured in 30-second increments, of 2,400 ml/hr. The rate of 2,400 ml/hr was chosen as a rate that is greater than that which is only possible through drug-induced diuresis or line clearance.[3]

Accounting for Periods of Diuresis. Acute surges because of diuretic administration were then eliminated by excluding those that were bounded by high flow rate of >250 ml/hr in 10 minutes before and after the acute surge. The minimum diuresis rate of 250 ml/hr and minimum duration of 10 minutes were chosen to decrease well within the known minimum diuresis rate and minimum diuresis period, respectively, after administration of furosemide.[3,4]

Surge Volume. Acute surges because of airlocks required urine output volume to be greater than maximum tubing retention volume for each system. The maximum tubing retention volume was chosen as the cutoff volume to disregard acute surges that corresponded to the emptying of the urine drain line alone and not urine retained in the bladder because of an airlock.

After exclusion of periods of diuresis and surge volumes less than the tubing retention volume, the remaining acute surges in UO were then determined to represent urine retained in the bladder associated with an airlock event. Periods of false oliguria were defined based on patient weight as urine flow of less than 0.5 ml/kg/hr for at least 30 minutes within the hour containing an airlock. Typical characteristics of an acute surge in urine output caused by the formation and breaking of an airlock are shown in Figure 2.

RESULTS

A total of 10 control devices and 10 test devices were studied. Fifteen of 18 patients were men. The average age of the control patients was 52 ± 6 years, and the average age of the test patients was 44 ± 7 years. The average weight of the control patient was 79.2 ± 6.0 kg, and the average weight of the test patient was 82.8 ± 5.0 kg. The mean % burn for control patients was 49 ± 9% and mean % burn for the test patient was 48 ± 7%. Note that one patient was being treated at the burn center, but was not a burn patient (patient 17 in Table 1). A 16-Fr urine catheter was used for all patients participating in the study.

Example urine output data in 5-minute average windows from a representative control case, representative test case, and extreme control case are shown in Figure 3A, B, and C, respectively. In Figure 3A, control patient 19 has an acute surge at 4:05 AM followed by a period of false oliguria, which is indicative of an airlock. A diuretic surge occurred between 1:30 AM and 2:30 AM was excluded for further analysis per criteria, but was also confirmed by the medical record. In Figure 3C, control patient 17 has a period of false oliguria because of both urine accumulating in drainage tubing and being retained in the bladder that lasted for 190 minutes, followed by a surge of 329 ml after the airlock was cleared at 10:03 PM.

Table 1. Line clearance surges and airlocks associated surges

Patient No.	Length Monitored (hr)	Line Clearance Surges			Airlocks		
		No.	Per Day	Average Surge Volume (ml)	No.	Per Day	Average Surge Volume (ml)
Control							
1	63.8	5	1.9	48.8	3	1.1	62
4	62.9	14	5.3	30.0	2	0.8	69.5
6	86.0	12	3.3	29.5	1	0.3	50
8	62.3	5	1.9	23.8	0	0.0	N/A
9	13.0	5	9.3	40.8	1	1.9	117
10	21.4	0	0.0	N/A	0	0.0	N/A
14	45.6	4	2.1	23.5	0	0.0	N/A
16	47.6	6	3.0	28.5	0	0.0	N/A
17	63.3	10	3.8	56.6	1	0.4	329
19	87.4	7	1.9	24.3	0	0.0	N/A
All	553.2	68	3.0	34.4	8	0.4	102.6
Test							
2	3.5*	1	6.9	21.0	0	0.00	N/A
3	101.3	6	1.4	24.2	0	0.00	N/A
5	79.2	0	0.0	N/A	0	0.00	N/A
7	30.2	3	2.4	21.0	0	0.00	N/A
11	91.1	1	0.3	21.0	0	0.00	N/A
12	19.6	0	0.0	N/A	0	0.00	N/A
13	24.1	1	1.0	21.0	0	0.00	N/A
15	90.2	5	1.3	24.0	0	0.00	N/A
18	89.2	5	1.3	22.8	0	0.00	N/A
20	45.9	1	0.5	21.0	0	0.00	N/A
All	574.2	23	1.0	22.9	0	0	N/A

N/A, not applicable; *UO*, urinary output.

*Because of a loose connected cable, data from the UO monitor were not captured by the data logger, resulting in shorter UO monitoring duration for patient 2.

Acute surges occurred in both the control group and the test group as detailed in Table 1. In the control group, 9 of 10 (90%) patients experienced at least 1 acute surge. In the test group, 8 of 10 (80%) patients experienced at least 1 acute surge. This difference was not statistically different (χ^2 test (1) = 0.40, $P = .53$). Control subjects experienced a total of 68 acute surges across 553.2 hours with surge volumes ranging from 21 to 329 ml and averaging 34.4 ± 4.8 ml. Test subjects experienced a total of 23 acute surges across 574.2 hours with surge volumes ranging from 21 to 27 ml and averaging 22.9 ± 0.5 ml. These correspond to statistically significant differences between control and test groups for both the number of surges ($P < .01$) and the surge volume ($P < .05$). Figure 4 describes the cumulative number of surges in both groups.

Airlocks were calculated by excluding acute surges less than the maximum tubing retention volumes in control and test groups (surge cutoffs of 40.8 and 32.2 ml, respectively; Figure 4). Surges greater than the cutoff values indicative of airlocks are detailed in Table 1. In the control group, 5 of 10 (50%) patients experienced a total of 8 airlocks and 6 associated periods of false oliguria across 553.2 hours. Airlock surge volumes ranged from 50 to 329 ml and averaged 102.6 ± 35.4 ml. False oliguria duration ranged from 31.9 to 190.2 minutes and averaged 79.1 ± 26.2 minutes. In the test group, patients did not experience airlocks, and hence there were no associated periods of false oliguria across 574.2 hours ($P < .05$).

DISCUSSION

The goal of our study was to examine the extent of preventable urinary retention in both the tubing and the bladder, along with the impact of a novel self-clearing drainage tubing system on urine output monitoring in an intensive care setting. Of note is that the burn ICU often has a particularly high nurse to patient ratio and substantial vigilance of urine output monitoring because of the extreme importance in guiding fluid therapy in this population. The nursing staff, as standard care, manipulated the urine drain line to break airlocks with each hourly recording of urine output, and the Criticore urine collection

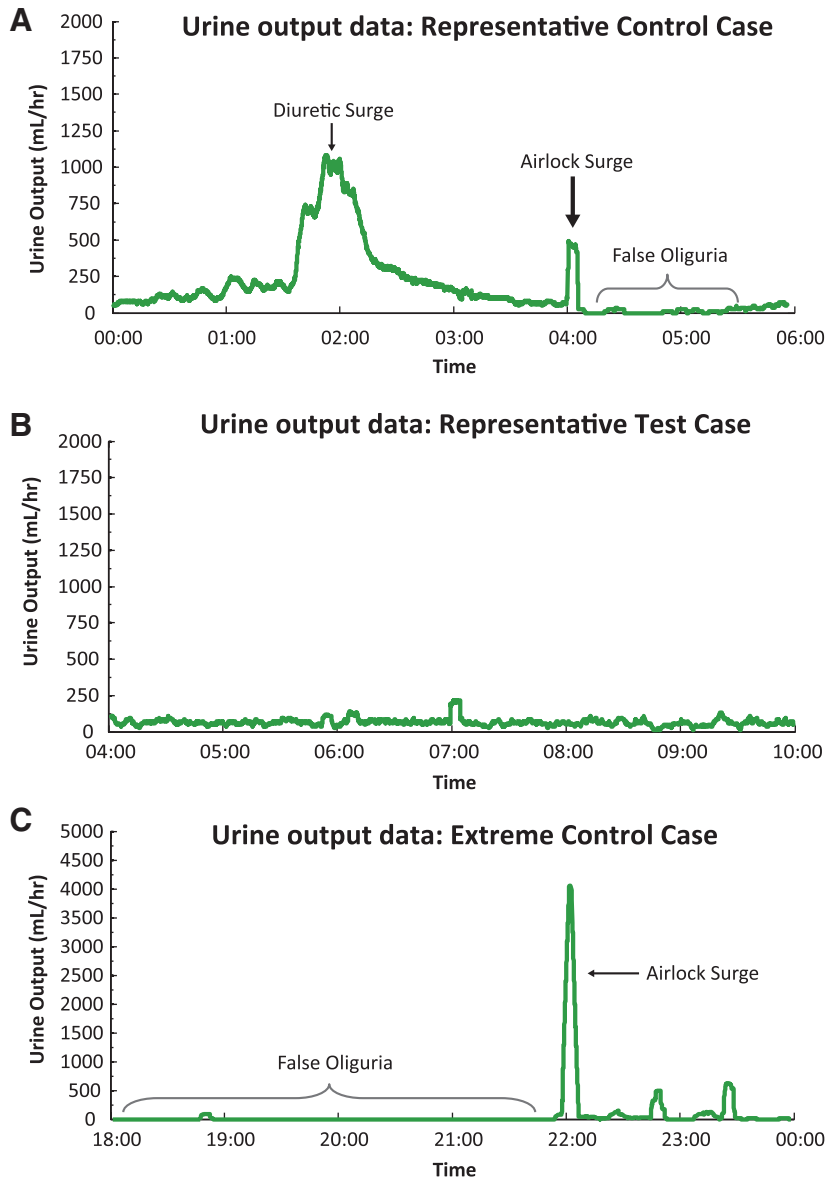

Figure 3. Example of urine production as measured by the urine output monitor in a 6-hour period. Rate (milliliter per hour) was calculated in 5-minute averages. A. Representative control patient data (patient 19) show an airlock as indicated by an acute surge in urine output at 4:05 AM followed by 37 minutes of false oliguria. A diuretic surge is shown to occur between 1:30 AM and 02:30 AM. B. Representative test patient data (patient 12) show no airlocks as evidenced by no acute surges. C. Data from a control patient (patient 17) with the largest surge shows 190 minutes of false oliguria because of an airlock followed by a 329-ml acute surge in urine output at 10:03 PM.

vessel was placed at or near the foot of the bed to minimize airlocks. However, based on the data in the control group, there were a few occasions when the urine drain line was not manipulated hourly (such as urine output data in Figure 3C). Accordingly, these results in the control group represent a reasonable estimation of best practices in the intensive care environment using existing urine output monitoring technology. Our study showed that airlocks and periods of false oliguria occur with standard drainage tubing. It also showed that this inaccuracy can be eliminated with an antiairlock drainage tube system, thereby allowing more accurate real-time urine output measurements.

Clinically, these periods of false oliguria are relevant in that they have the potential to manifest either as a false negative or a false positive for oliguria. If the acute surge of urine after airlock clearing occurs during a true new-onset period of oliguria, the surge can hide it (false negative). If an airlock

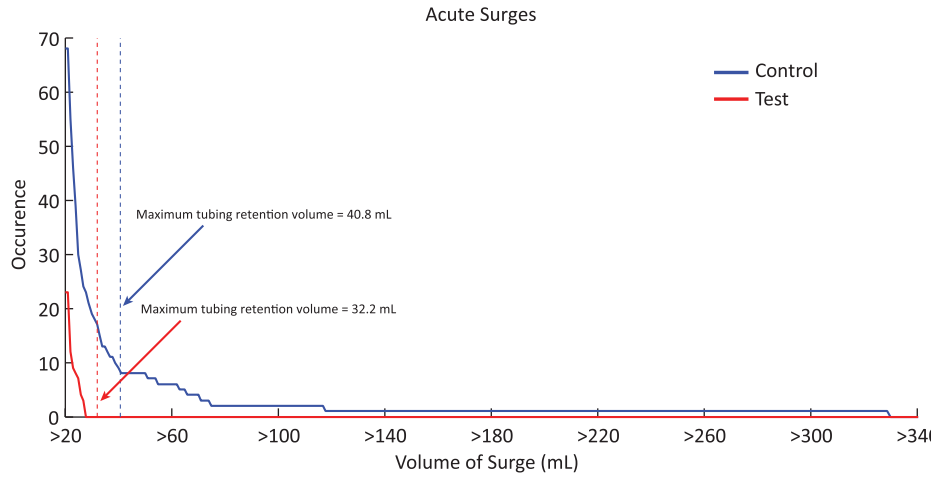

Figure 4. Number of surges versus their volume in test and control groups. Surges indicative of airlock formation are greater than the maximum tubing retention volume cutoff values shown by dashed lines for each group.

impedes normal urine drainage resulting in urinary retention, it appears as a false oliguria (false positive). This uneven and inaccurate urine output measurement can directly affect clinical diagnosis and decision making. For example, the detection of AKI relies on detecting oliguria measured hourly, along with the changes in serum creatinine measured daily.[5,6] False negatives in assessing oliguria, caused by an acute surge above the AKI threshold because of an airlock, can lead to a failure to detect AKI. Furthermore, false positives in assessing oliguria decrease the reliability of the urine output criteria and result in inappropriate alerts, both of which erode medical staff confidence in this metric. Indeed, the overall reliability of the urine output criteria for AKI has been questioned and frequently neglected.[7–10] This is despite the fact that several studies have shown that omitting the urine output criterion leads to an under diagnosis of AKI.[9,10] Compared with serum creatinine, the changes in urine output have been shown to be the more sensitive and early marker of AKI,[9–11] and even mild oliguria is associated with an increase in ICU mortality.[12]

Despite its recognition as a valuable marker of kidney function, the difficulty of implementing accurate hourly measurements of urine output has understandably led to a range of conclusions regarding the appropriate duration of oliguria to reliably detect AKI; from 2 to 3 hours,[13] to 3 to 5 hours,[14] and even longer to 6 hours.[6] The value of UO monitoring in acute kidney dysfunction and injury should be reexamined with eUOMs utilizing self-clearing drainage systems.

Accurate real-time UO measurements will be necessary for the development of effective closed-loop burn resuscitation technologies. Although standard of care adjustment of infusion rate for burns occurs every hour, the renal response to large changes in fluid infusion is likely much quicker. High-resolution electronic UO monitors have the potential for timely detection of recent and transient events such as brief periods of oliguria or anuria, rapid response to fluid or diuretic challenges, and more rapid detection of AKI. This will allow for multiple hourly adjustments in infusion rate to hold UO levels in the range of clinical targets.[15–18] Thus, measuring real-time UO and using control algorithms for closed-loop control may provide a means for superior burn resuscitation and lower the incidence of fluid creep. Minimizing the artifacts of urine retention in the drainage tube and bladder may be required to optimize the performance of closed-loop algorithms.

Importantly, manual manipulation of the drainage lines to clear airlocks also increases the workload for the medical staff, the amount of urethral trauma, and the risk of suction trauma to the bladder mucosa itself.[19–21] This latter trauma has been linked to UTI.[22,23]

Drainage line manipulation to break airlocks is required with all commercially available urine drainage systems and is an artifact of the diameter of the urine drainage tube. The collection vessel, ie, polyvinyl chloride (PVC) bag, rigid urimeter or eUOM (such as the Bard Criticore), only influences the formation and breaking of airlocks insomuch as it alters the course of the drainage tube and the formation of dependent loops.

In an effort to address the problem of airlocks, Garcia et al[2] developed a spiral shaped drainage tube that, when properly positioned, was able to eliminate

airlocks. Further study of the device, although, found that it was particularly susceptible to developing multiple airlocks if the spiral portion of the tube was laid on its side and its development was discontinued.

As with any new technology, the potential for added cost is a topic of concern to the healthcare community. The technology must be competitively priced compared with other electronic urine monitors and drainage sets. In addition to hard costs, the Accuryn System is expected to reduce nursing burden by 1) automatically breaking airlocks and 2) automatically uploading data to the electronic health record.

This study has some notable limitations. In particular, it is a small pilot trial with 18 patients at 2 sites that is limited to the burn ICU. The study also uses a prototype version of the Accuryn System for the purposes of exploring the effects of airlocks on urine output. The current version of the device incorporates significant improvements (such as weight, size, and shape), along with integration of the airlock clearing mechanism with urine output measurement functionality to enable widespread use in the hospital setting. Nevertheless, the study points out a significant issue in patient care and provides a foundation for further research.

CONCLUSIONS

The results from our study demonstrate that, even in the attentive setting of the burn unit, data from the electronic UO monitoring can be corrupted by urine retention and airlocks. In this two-center study, we demonstrated that automated drainage tubing clearance reduces the occurrence of airlocks and the accompanying acute surges and periods of false oliguria. This has the potential to improve tracking of real-time urine output, decrease caregiver workload, speed up the detection of AKI, reduce hospital acquired UTIs, and allow computerized decision support. The results call for further research into the use of electronic UO monitoring in patient populations where fluid resuscitation and monitoring of urine output are critical.

ACKNOWLEDGMENTS

Carin Lindquist (Theranova, LLC), Charles Mitchell (University of Texas Medical Branch), Farrah Parker (Augusta), and Yvonne Daniel (Augusta) assisted in running the study and the acquisition of data from the sites. Keyur Mehta (Theranova, LLC) and Marcie Hamilton (Theranova, LLC) assisted with initial concept and study design.

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