Submitted: 01 May, 2021 Accepted: 31 May, 2021 Published: 08 May, 2022 DOI:10.22514/sv.2021.121

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ORIGINAL RESEARCH

Standard effluent potassium concentration as a predictive factor for postreperfusion significant arrhythmias in deceased liver transplantation

Liang Zhang[1], Fu-Shan Xue[1], Ming Tian[1,*], Zhi-Jun Zhu[2,*]

[1]Department of Anesthesiology, Beijing Friendship Hospital, Capital Medical University, 100050 Beijing, China
[2]Liver Transplantation Center, National Clinical Research Center for Digestive Diseases, Beijing Friendship Hospital, Capital Medical University, 100050 Beijing, China

***Correspondence**
tianmingbfh@gmail.com
(Ming Tian);
zhu-zhijun@outlook.com
(Zhi-Jun Zhu)

Abstract

Postreperfusion significant arrhythmias (PRSA), which is known as part of the diagnostic criteria for postreperfusion syndrome, may serve as a precursor of postreperfusion cardiac arrest (PRCA). Considering the possible relationship between the use of liver grafts with high effluent potassium (eK^+) concentrations and PRCA, we aimed to investigate the role of eK^+ in PRSA development in deceased liver transplantation (LT). Using the prospectively collected data from a prior observational study, a retrospective study of 91 adult LT recipients with eK^+ measurements between November 2016 and December 2018 was conducted to determine the incidence, predictors, and outcomes of PRSA. PRSA occurred in 46 cases (50.5%), and PRCA occurred in 8 patients (8.8%). Multivariable analysis demonstrated elevated eK^+ concentration before reperfusion (odds ratio [OR], 1.425; 95% confidence interval [CI] 1.134–1.790; $P = 0.002$), and higher serum potassium level at one minute following reperfusion (sK^+_1) (OR, 3.244; 95% CI 1.668–6.380; $P = 0.001$) as independent risk factors for PRSA. An $eK^+ \geq 6.9$ mmoL/L could predict PRSA with a sensitivity of 71.7% and a specificity of 80.0% (area under the receiver-operating characteristics curve [AUROC], 0.828). In comparison, an $sK^+_1 \geq 5.5$ mmoL/L could predict PRSA with a sensitivity of 87.0% and a specificity of 64.4% (AUROC, 0.810). PRSA was associated with increased risks of PRCA, postreperfusion vasoplegia, and postoperative early allograft dysfunction. This study has demonstrated that eK^+ has the potential to predict PRSA in deceased LT.

Keywords

Potassium; Effluent; Hyperkalemia; Arrhythmias; Cardiac arrest; Postreperfusion syndrome; Liver transplantation

1. Introduction

Postreperfusion cardiac arrest (PRCA) occurs in 1.0% to 8.3% of patients undergoing liver transplantation (LT) and is associated with high intraoperative and postoperative mortality [1–8]. Previous studies have identified several risk factors for PRCA, including postreperfusion syndrome [4–7], hyperkalemia [5–8], and pulmonary embolism [5, 6]. Moreover, numerous case series have documented anaphylaxis [9], intracardiac thrombus [10], and acute myocardial infarction [11] as relatively uncommon causes of PRCA.

However, studies regarding PRCA and the associated risk factors were generally limited by their small sample size and single-center settings. In addition, none of these studies has assessed the effect of standard effluent potassium (eK^+) concentration [12, 13], which may represent excessive potassium ions releasing from liver grafts, on postreperfusion significant arrhythmias (PRSA) and PRCA in deceased LT.

We, therefore, aimed to investigate the relationship between the eK^+ concentration before reperfusion and the development of PRSA and PRCA, based on the hypothesis that the occurrence of PRSA is a prodrome of PRCA.

2. Methods

This study was approved by the Institutional Review Board of Beijing Friendship Hospital, Beijing, China (No.2020-P2-042-01), and the requirement for written informed consent was waived due to its retrospective nature. The research is in accordance with the Helsinki Declaration of 1975, as revised in 2010.

2.1 Study population

We retrospectively reviewed the medical records of 147 consecutive adults aged ≥18 years who underwent deceased LT between November 2016 and December 2018. Exclusion criteria were no intraoperative eK^+ measurement (n = 55) and insufficient data (n = 1). A total of 91 cases were counted in

the final analysis.

2.2 Anesthetic and surgical techniques

The anesthetic and surgical techniques were conducted according to institutional protocols as previously described [12]. The anesthetic techniques typically consisted of intravenous induction and combined intravenous and inhalational maintenance. Intraoperative invasive monitors included a radial arterial line, a triple-lumen central venous catheter, and a pulmonary arterial catheter. For surgical techniques, cross-clamping of the inferior vena cava (IVC) without veno-venous bypass was used in all cases. Just before the infrahepatic IVC anastomosis was completed, the graft was rinsed free of the University of Wisconsin (UW) solution with 5% albumin through the portal vein (PV) with a flush volume of 1 mL/gram of allograft tissue. Just before the PV flush was finished, the effluent samples were directly aspirated into a 5-mL syringe and were immediately analyzed for the standard eK^+ concentrations using a point-of-care blood gas analyzer (Fig. 1). Electrolytes and blood gas were routinely monitored at the following time points: before incision, before PV clamping, before reperfusion, one minute following reperfusion, 5 minutes following reperfusion, one hour following reperfusion, 2 hours following reperfusion, and at the end of the operation.

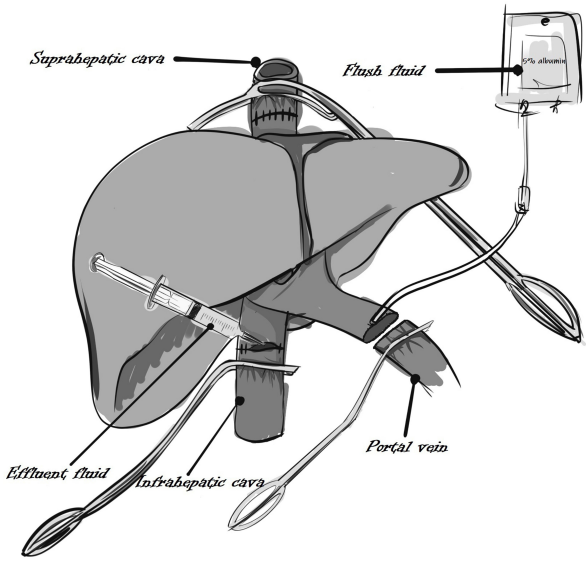

FIGURE 1. Schematic of the collection of effluent samples for standard effluent potassium concentration analysis.

2.3 Data acquisition

All clinical data of these patients, including patient and graft characteristics, intraoperative variables, and postoperative outcomes, were gathered from our institutional medical records. The following patient and graft characteristics were included: age, sex, body weight, height, Child-Pugh score, Model for End-Stage Liver Disease (MELD) score, indications for LT, graft weight, graft-to-recipient weight ratio (GRWR), cold ischemia time, warm ischemia time, and the presence of an expanded criteria donor (ECD) liver graft; Intraoperative variables included intraoperative serum potassium (sK^+) levels, standard eK^+ concentration, incidences of PRSA, severe postreperfusion syndrome, PRCA, and postreperfusion vasoplegia, and vasopressor requirements for severe postreperfusion syndrome during the reperfusion period; Postoperative data included mechanical ventilation time, length of hospital and intensive care unit (ICU) stay, early allograft dysfunction, acute kidney injury, re-operation, and in-hospital mortality within the first 30 days post-LT.

2.4 Definitions of outcomes

The definitions of PRSA and postreperfusion vasoplegia were used according to the Peking criteria for severe postreperfusion syndrome [14]. PRSA was diagnosed when one or more of the following variables were present: a $\geq$15% decrease in heart rate from the baseline, new-onset hemodynamically significant arrhythmias, or cardiac arrest requiring cardiac massage. Postreperfusion vasoplegia was defined as a mean arterial pressure $<$50 mmHg, cardiac index $>$2.5 L/min/m^2, and systemic vascular resistance $<$800 dyne/s/cm^5 that occurred during the late reperfusion period and required more than 0.5 μg/kg/min of norepinephrine infusion. Acute kidney injury and early allograft dysfunction were generally identified according to the Kidney Disease: Improving Global Outcomes (KDIGO) guidelines [15] and Olthoff's definition [16], respectively.

2.5 Statistics

Continuous variables are described as the mean $\pm$ standard deviation or median (interquartile range), and the intergroup comparisons were conducted by the Student's *t*-tests or Mann-Whitney U tests. Categorical variables were described as frequencies and percentages, and the intergroup comparisons were performed using Pearson's chi-squared test or Fisher's exact test. To identify the independent predictors for PRSA, potentially significant variables, which had a P value < 0.10 in the univariate analysis, were further analyzed by stepwise binary logistic regression. The performance and the best cut-off value of the independent predictors for PRSA were assessed by the receiver operator characteristic (ROC) curve. At the best cut-off point, the sensitivity, specificity, positive (PPV), and negative (NPV) predictive values were calculated. Statistical analyses were performed using SPSS software Version 22.0 (SPSS, Inc., Chicago, IL, USA). All statistical tests were 2-sided, and a P value < 0.05 was considered statistically significant.

3. Results

3.1 Baseline characteristics

The most common indications for LT in this study were hepatitis B virus cirrhosis (50.5%), and 27 of 91 cases (29.7%) were combined hepatocellular carcinoma. The mean age of the patients (63 males and 28 females) was 49.4 $\pm$ 10.8 years. The median (range) Child-Pugh score and MELD score were 9 (5–15) and 15 (6–38), respectively. The median (range) eK^+ concentration was 6.7 (2.6–24.2) mmoL/L. The other baseline characteristics are summarized in Table 1.

TABLE 1. Baseline characteristics of study patients in our cohort.

	No.	Mean ± SD	Median (range)
Gender			
Male	63		
Female	28		
Primary diagnosis			
Hepatitis B	46		
Hepatitis C	3		
Alcoholic	11		
Cholestatic	12		
Cryptogenic	2		
Others	17		
Combined HCC	27		
Age (yr)	91	49.4 ± 10.8	
Height (cm)	91		170 (150–193)
Weight (kg)	91	66.2 ± 14.9	
Child-Pugh score	91		9 (5–15)
MELD score	91		15 (6–38)
Graft weight (g)	91	1314 ± 273	
GRWR (%)	91		1.94 (1.05–4.43)
CIT (min)	91	509.2 ± 133.6	
WIT (min)	91		38 (25–66)
eK^+ (mmoL/L)	91		6.7 (2.6–24.2)

CIT, cold ischemia time; eK^+, effluent potassium concentration; GRWR, graft-to-recipient weight ratio; HCC, hepatocellular carcinoma; MELD, Model for End-Stage Liver Disease; SD, standard deviation; WIT, warm ischemia time.

3.2 PRSA and risk factors

Forty-six (50.5%) patients experienced PRSA. The following variables differed significantly between the non-PRSA and PRSA groups: graft weight (1200 [1090, 1411] vs. 1385 [1235, 1589] g, P = 0.004), GRWR (1.76 [1.50, 2.22] vs. 2.05 [1.85, 2.53] %, P = 0.003), ECD graft proportion (6.7% vs. 30.4%, P = 0.004), level of sK^+ at one minute following reperfusion (sK^+_1) (5.31 ± 0.82 vs. 6.38 ± 0.87 mmoL/L, P < 0.001), and eK^+ concentration (5.70 [4.35, 6.75] vs. 8.65 [6.58, 12.90] mmoL/L, P = 0.003) (Table 2). Multivariate logistic analysis revealed that higher eK^+ concentration (OR (odds ratio), 1.425; 95% CI (confidence interval), 1.134–1.790; P = 0.002), and sK^+_1 level (OR, 3.244; 95% CI, 1.668–6.308; P = 0.001) were found to be independent risk factors of PRSA (Table 3).

3.3 Predictive ability of eK^+ for PRSA

Based on the area under the ROC curves (AUROCs), the eK^+ concentration had the best predictive ability for the presence of PRSA (AUROC, 0.828), followed by the sK^+_1 level (AUROC, 0.810) (Fig. 2). Table 4 shows the sensitivity, specificity, PPV, NPV, and diagnostic accuracy at the cut-off point providing the best Youden index for each variable. The best cut-off point for eK^+ was more than 6.9 mmoL/L, giving a sensitivity of 71.7%, specificity of 80.0%, PPV of 79.6%, and NPV of 73.5% (Table 4).

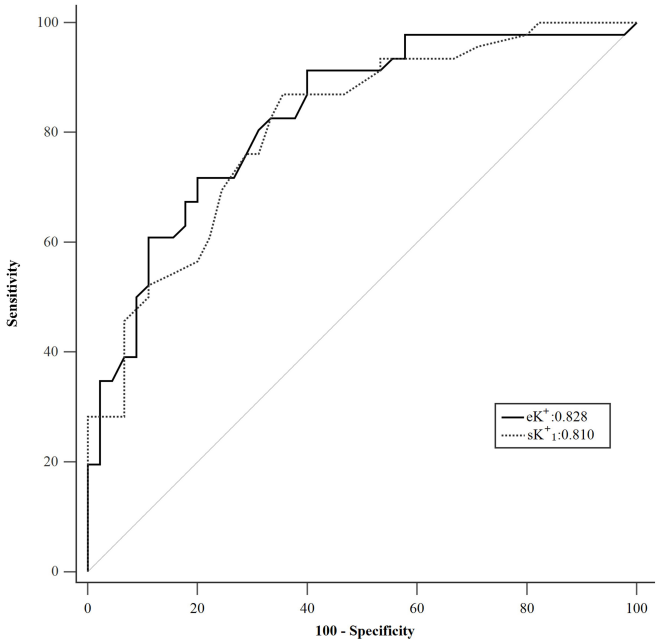

FIGURE 2. ROC curve analysis to predict the occurrence of postreperfusion significant arrhythmias in 91 consecutive decease liver transplant recipients. eK^+, effluent potassium concentration; sK^+_1, serum potassium concentration at one minute following reperfusion; ROC, receiver operating characteristic.

3.4 PRSA and associated outcomes

No statistically significant differences were found in severe postreperfusion syndrome occurrence between groups (Table 2). However, the occurrences of PRCA and postreperfusion vasoplegia were significantly higher in the PRSA group (17.4% vs. 0.0%, P = 0.006; 21.7% vs. 6.7%, P = 0.040, respectively), and epinephrine requirements for severe postreperfusion syndrome were significantly increased in the PRSA group (0.28 [0.13, 0.41] vs. 0.13 [0.11, 0.23] μg/kg, P = 0.004). Moreover, postoperative early allograft dysfunction occurred significantly more frequently in the PRSA group than the non-PRSA group (65.2% vs. 22.2%, P < 0.001). There were no significant differences for any of the other outcomes, including mechanical ventilation time, lengths of ICU and hospital stay, acute kidney injury occurrence, in-hospital mortality, and re-operation rate (Table 2).

4. Discussion

Very little data can be found in the literature concerning the roles of eK^+ in the development of PRSA and PRCA in deceased LT. In the present study, we found that the value of eK^+ higher than 6.9 mmoL/L demonstrated a higher probability of PRSA. Thus, our findings support that

TABLE 2. Clinical characteristics and outcomes in patients with and without postreperfusion significant arrhythmias.

Variables	No PRSA (n = 45)	PRSA (n = 46)	*P* Value
Characteristics			
Age (y)	49.8 ± 10.7	49.1 ± 11.0	0.770
Male gender (n, %)	32 (71.1)	31 (67.4)	0.701
Height (cm)	170.0 (165.0–175.5)	171.0 (159.5–174.3)	0.679
Weight (kg)	67.3 ± 15.7	65.1 ± 14.1	0.492
Child-Pugh score	9.0 (6.5–12.0)	9.0 (6.0–11.0)	0.570
MELD score	16.3 ± 8.7	15.0 ± 6.3	0.448
Graft weight (g)	1200 (1090–1411)	1385 (1235–1589)	0.004
GRWR (%)	1.76 (1.50–2.22)	2.05 (1.85–2.53)	0.003
CIT (min)	490.5 ± 140.5	527.5 ± 125.3	0.188
WIT (min)	38 (34–46)	38 (35–41)	0.058
ECD graft (n, %)	3 (6.7)	14 (30.4)	0.004
eK^+ (mmoL/L)	5.70 (4.35–6.75)	8.65 (6.58–12.90)	<0.001
sK^+_0 (mmoL/L)	4.10 (3.80–4.60)	4.20 (3.88–4.90)	0.532
sK^+_1 (mmoL/L)	5.31 ± 0.82	6.38 ± 0.87	<0.001
sK^+_5 (mmoL/L)	3.65 ± 0.65	4.21 ± 1.04	0.003
Outcomes			
PRCA (n, %)	0 (0.0)	8 (17.4)	0.006
PRV (n, %)	3 (6.7)	10 (21.7)	0.040
Severe PRS (n, %)	19 (42.2)	27 (58.7)	0.116
EP dose for severe PRS	0.13 (0.11–0.23)	0.28 (0.13–0.41)	0.004
NE dose for severe PRS	0.10 (0.05–0.20)	0.11 (0.05–0.30)	0.076
Ventilation time (hours)	4.0 (2.6–5.1)	4.0 (2.3–6.6)	0.818
Length of ICU stay (days)	3.4 (2.6–4.3)	3.1 (2.5–3.8)	0.653
Hospitalization time (days)	20.0 (14.0–24.0)	20.0 (15.8–31.3)	0.467
EAD (n, %)	10 (22.2)	30 (65.2)	<0.001
AKI (n, %)	21 (51.2)	21 (48.8)	0.827
Re-operation (n, %)	3 (6.7)	4 (2.2)	0.361
In-hospital mortality (n, %)	4 (8.9)	4 (8.7)	1.000

AKI, acute kidney injury; CIT, cold ischemia time; EAD, early allograft dysfunction; ECD, expanded criteria donor; eK^+, effluent potassium concentration; EP, epinephrine; GRWR, graft-to-recipient weight ratio; ICU, intensive care unit; MELD, Model for End-Stage Liver Disease; NE, norepinephrine; PRCA, postreperfusion cardiac arrest; PRS, postreperfusion syndrome; PRSA, postreperfusion significant arrhythmias; PRV, postreperfusion vasoplegia; sK^+_0, serum potassium concentration before reperfusion; sK^+_1, serum potassium concentration at one minute following reperfusion; sK^+_5, serum potassium concentration at five minutes following reperfusion; WIT, warm ischemia time.

TABLE 3. Multivariate logistic regression analysis: independent risk factors associated with the presence of postreperfusion significant arrhythmias in deceased liver transplantation.

	OR	95% CI	*P* Value
eK^+	1.425	1.134–1.790	0.002
sK^+_1	3.244	1.668–6.308	0.001

CI, confidence interval; eK^+, effluent potassium concentration; sK^+_1, serum potassium concentration at one minute following reperfusion; OR, odds ratio.

elevated eK^+ is a potentially modifiable risk factor for PRSA occurrence, especially during LT from ECD liver grafts.

Previous studies revealed a 1.0% to 8.3% incidence of PRCA in adult LT [1–7]. However, the incidence rate reported in the present study was a little higher with no intraoperative death, but in a large national LT center where ECD liver grafts were frequently encountered; we speculate that this may reflect the roles of eK^+ in early warning of PRSA and subsequent development of PRCA. Noteworthily, all PRCA cases in our study occurred in patients who suffered from PRSA. Hence, these findings partly corroborate the hypothesis that PRSA may serve as a prodrome of PRCA during LT.

Consistent with the previous studies, intraoperative hyperkalemia was a well-known risk factor for adverse outcomes [17] and was significantly associated with postreperfusion syndrome [18–21] and PRCA [5–8] in adult LT. Nonetheless, the influences of peak serum potassium levels following reperfusion on the development of postreperfusion syndrome and PRCA were often underestimated due to the lack of a real-time continuous monitoring strategy. Besides, postreperfusion syndrome was the most frequently reported intraoperative risk factor associated with PRCA in previous studies [4–7].

TABLE 4. Prediction of postreperfusion significant arrhythmias in 91 consecutive patients who underwent deceased liver transplantation.

	AUROC	Cut-off point	Sensitivity, %	Specificity, %	PPV	NPV
eK^+	0.828	6.9	71.7	80.0	78.6	73.5
sK^+_1	0.810	5.5	87.0	64.4	71.4	82.9

AUROC, area under the receiver operator characteristic curve; eK^+, effluent potassium concentration; NPV, negative predictive value; PPV, positive predictive value; sK^+_1, serum potassium concentration at one minute following reperfusion.

However, it is still controversial whether PRCA is just a part of postreperfusion syndrome [14] or the most severe form of postreperfusion syndrome [18], which depends on the diagnostic criteria used to define postreperfusion syndrome. In the present study, the diagnosis of PRCA was based on the Peking criteria for severe postreperfusion syndrome [14], in which PRCA and postreperfusion vasoplegia were regarded as the most severe manifestations of arrhythmias and hypotension, respectively. Consequently, PRSA has been associated with increased risks of PRCA and postreperfusion vasoplegia and epinephrine requirements for severe postreperfusion syndrome.

Recently, numerous published case series [1, 2] have shown that the quality of liver grafts is associated with PRCA, especially during LT from donation after circulatory death or macrosteatotic liver grafts. In this study, multivariable regression modeling also identified one graft-related predictor of PRCA: the eK^+ concentration before reperfusion. However, the multitude of observational studies [3, 4] could not identify an independent graft-related risk factor of PRCA. The reason for the conflicting results regarding the impact of graft quality on PRCA remains unclear, probably because most studies targeted intraoperative cardiac arrest rather than PRCA.

Unlike previous studies [4, 7], we did not ascertain an association between MELD score and intraoperative cardiac arrest in the present study. Perhaps most candidates with low MELD scores were listed for LT during the study period, potentially leading to selection bias in our study. Regarding patient-related factors, QTc interval prolongation [22] and inducible left ventricular outflow tract obstruction [23] were also reported to be associated with intraoperative cardiac arrest and postoperative mortality.

Although the exact mechanism has not been elucidated, excessive potassium ions released from liver grafts following reperfusion, which can be quantified by the standard eK^+ concentration, might have played an essential role in the development of postreperfusion hyperkalemia, PRSA, and PRCA. In our prior study [12], a strong correlation between eK^+ and donor risk index has been demonstrated. To our experience, the standard eK^+ concentration may serve as an indicator of the severity of the hepatic ischemia-reperfusion injury and may be responsible for the difference in postoperative early allograft dysfunction occurrence. More specifically, when an ECD or high eK^+ liver graft is implanted, postreperfusion hyperkalemia caused by the excessive release of potassium ions may be responsible for PRSA and PRCA. In contrast, the inflammatory storm induced by excessive release of proinflammatory cytokines [24] may be responsible for postreperfusion refractory hypotension and vasoplegia.

This study has several limitations. First, the retrospective nature of this single-center study may have resulted in an inherent selection bias, which potentially limits the generalizability of our findings. Second, new-onset PRSA occurred in the immediate reperfusion period was used instead of PRCA due to its low incidence rate; therefore, multicenter, large-sample, prospective randomized controlled studies are needed to confirm the effect of eK^+ on PRCA. Third, although hyperkalemia-related arrhythmias were responsible for all PRCA cases in this study, other potential causes, such as fat embolism, intracardiac thrombus, and anaphylaxis, should not be ignored. Finally, potential therapeutic interventions, such as graft flushing techniques [25], a speed-controlled reperfusion strategy [26], and simultaneous pretreatment with calcium and epinephrine, warrant further confirmation in future studies.

5. Conclusions

In summary, we demonstrated that both the standard eK^+ concentration before reperfusion and the sK^+_1 level following reperfusion were independent predictors for PRSA in deceased LT. Therefore, LT surgeons and anesthesiologists should keep those newly identified risk factors in mind when preparing for graft reperfusion.

AUTHOR CONTRIBUTIONS

(I) Concept and design: LZ, FSX, MT, ZJZ. (II) Supervision: MT, FSX, ZJZ. (III) Materials, data collection, literature search, manuscript writing and fundings: LZ. (IV) Data analysis and interpretation: LZ, FSX, MT. (V) Critical revision: FSX, MT, ZJZ.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was approved by the Institutional Review Board of Beijing Friendship Hospital, Beijing, China (No.2020-P2-042-01), and the requirement for written informed consent was waived due to its retrospective nature. The research is in accordance with the Helsinki Declaration of 1975, as revised in 2010.

ACKNOWLEDGMENT

Thanks to all the peer reviewers for their opinions and suggestions.

FUNDING

This study was supported by the Research Foundation of Beijing Friendship Hospital (Grant No. YYQDKT 2018-12).

CONFLICT OF INTEREST

The authors declare no conflict of interest. Ming Tian is a Guest Editor of this journal.

DATA AVAILABILITY

The datasets obtained and/or analyzed during the current study are available from the corresponding author on reasonable request.

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How to cite this article: Liang Zhang, Fu-Shan Xue, Ming Tian, Zhi-Jun Zhu. Standard effluent potassium concentration as a predictive factor for postreperfusion significant arrhythmias in deceased liver transplantation. Signa Vitae. 2022; 18(3): 75-80. doi:10.22514/sv.2021.121.