Original Article

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System of integrating biosignals during hemodialysis: the CONTINUAL (Continuous mOnitoriNg viTal sIgN dUring hemodiALysis) registry

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Background: Appropriate monitoring of intradialytic biosignals is essential to minimize adverse outcomes because intradialytic hypotension and arrhythmia are associated with cardiovascular risk in hemodialysis patients. However, a continuous monitoring system for intradialytic biosignals has not yet been developed.

Methods: This study investigated a cloud system that hosted a prospective, open-source registry to monitor and collect intradialytic biosignals, which was named the CONTINUAL (Continuous mOnitoriNg viTal sIgN dUring hemodiALysis) registry. This registry was based on real-time multimodal data acquisition, such as blood pressure, heart rate, electrocardiogram, and photoplethysmogram results.

Results: We analyzed session information from this system for the initial 8 months, including data for some cases with hemodynamic complications such as intradialytic hypotension and arrhythmia.

Conclusion: This biosignal registry provides valuable data that can be applied to conduct epidemiological surveys on hemodynamic complications during hemodialysis and develop artificial intelligence models that predict biosignal changes which can improve patient outcomes.

Keywords: Biosignal, Cardiac arrhythmias, Hypertension, Hypotension, Renal dialysis

Introduction

End-stage kidney disease is an increasing burden for global health care, such that approximately 2.6 million patients are receiving dialysis worldwide and this number is expected to more than double in 2030 [1]. Approximately

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80% to 90% of end-stage kidney disease patients receive hemodialysis and the rest undergo peritoneal dialysis or transplantation [2,3]. Hemodialysis frequently leads to hemodynamic instability and autonomic imbalances, which predispose patients to intradialytic complications, such as hypotension, hypertension, and arrhythmia [4]. These hemodynamic events ultimately lead to cardiovascular death, which is the most common cause of death after starting hemodialysis, and accounts for more than 40% of deaths [5,6]. According to the United States Renal Data System database, among hemodialysis patients, arrhythmia is responsible for up to 60% and 20% of cardiovascular and all-cause deaths, respectively [7,8]. Accordingly, appropriate monitoring of hemodynamic complications during hemodialysis is essential to prevent adverse outcomes.

A biosignal is a physiological sign, such as blood pressure (BP), heart rate (HR), electrocardiogram (ECG) results, cardiac output, central venous pressure, heart rhythm, electroencephalogram, electrolytes, sympathetic nerve activity, and respiratory rhythms [9,10]. Monitoring biosignals increases the awareness of their clinical importance because they can serve as indicators for unpredictable events during routine or urgent practice. Hemodialysis *per se* changes the biosignals of patients with or sometimes without symptoms, and thus monitoring changes in biosignals may allow for tracing or predicting hemodynamic complications during hemodialysis [11–13]. Some studies have traced intradialytic biosignals such as BP and ECG, and the risk of hemodynamic complications and relevant outcomes could be identified in detail by monitoring these signals [8,14–16]. Nevertheless, intradialytic biosignals other than BP have been underutilized because systems that coordinate detection and storage have not been established in most centers.

To improve care quality and patient outcomes during hemodialysis, a system that integrates and utilizes biosignals should be incorporated into clinical practice. Regarding ECG, devices such as implantable loop recorders [8,14,15], Holter ECGs [16], and adhesive single-lead patches [17] could be applied during hemodialysis, but the clinical accessibility and applicability have not been validated. Herein, we developed system that integrated conventional monitoring of BP, HR, ECG, and photoplethysmogram with peripheral oxygen saturation (SpO_2), which was used to provide information to the cloud-based CONTINUAL (Continuous mOnitoriNg viTal sIgN dUring hemodiALysis) registry. This registry can be utilized in future studies to apply intradialytic biosignals in epidemiological surveys on hemodynamic complications and to develop artificial intelligence models with biosignals to predict relevant cardiovascular risks.

Methods

Ethical considerations

This study protocol was approved by the Institutional Review Board (IRB) of the Seoul National University Hospital in Seoul, Republic of Korea (No. 2005-018-1121) and was conducted in accordance with the principles of the Declaration of Helsinki. The registry did not include personal information such as name and unique identification information. The requirement to obtain informed consent from the patients was waived by the IRB.

Aim and study design

The system was established in the hemodialysis facility of the Seoul National University Hospital, which has maintained the biosignal registry since September 2020. Two categories of datasets were collected and could be merged, including hemodialysis-setting data from electronic medical records and real-time biosignal data from bedside monitoring. The former data included hemodialysis dates, times to start and end, the target value of the blood filtration rate and ultrafiltration, and the components and temperature of the dialysates and anticoagulants. The information was stored in Microsoft Excel format (Fig. 1A).

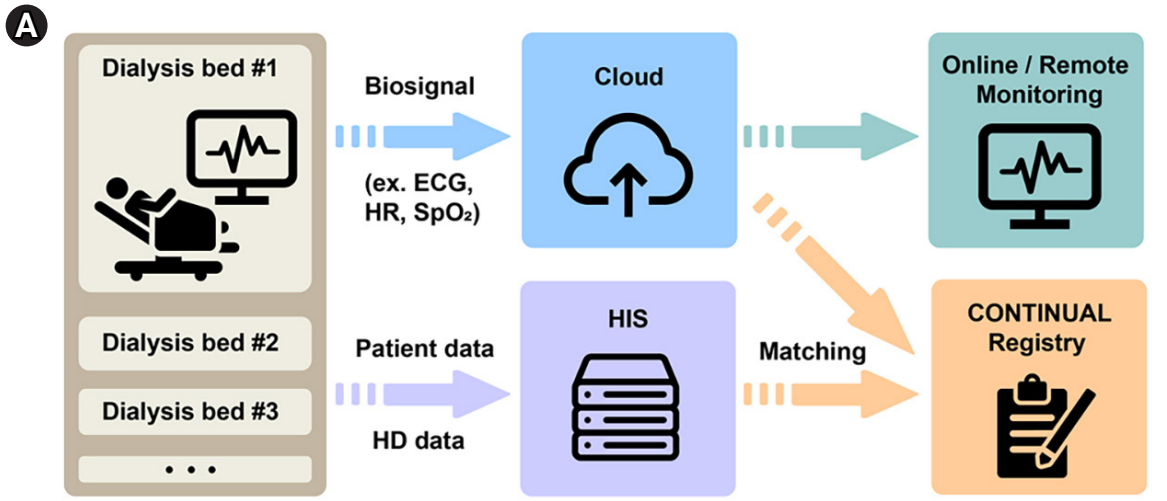
Study population

The registry consisted of adult patients (aged ≥18 years) who received vital sign monitoring with the developed system regardless of the reason for hemodialysis.

Data collection

Bedside monitors (Solar 8000i; GE Healthcare, Waukesha, WI, USA) produced the biosignals, including BP, HR, ECG, and SpO_2 by photoplethysmogram. For three-lead values

for all patients, two electrodes were placed below the right and left clavicles, and the other electrode was placed on the left lower chest. The bandpass filter for ECG ranged from 0.05 to 40 Hz. Values of changes in the ST segment, either elevation or depression, were also measured. Waveform biosignals such as ECG and photoplethysmogram were sampled at 500 Hz and updated every 2 seconds. Fig. 1A shows the overall system integration and delivery of intradialytic biosignals to the cloud, wherein the Vital Recorder program was applied [18]. Fig. 1B shows a repre-



Order	Date	Start time	End time	Target UF	Final UF	BFR	AC	Dialysate components			
								Na	K	HCO_3	Bath Temp
1	yyyy-mm-dd	OO:OO	OO:OO	O.O	O.O	OOO	Heparin	OOO	O.O	OO	OO.O
2	yyyy-mm-dd	OO:OO	OO:OO	O.O	O.O	OOO	Nafamostat	OOO	O.O	OO	OO.O
3	yyyy-mm-dd	OO:OO	OO:OO	O.O	O.O	OOO	None	OOO	O.O	OO	OO.O
4	yyyy-mm-dd	OO:OO	OO:OO	O.O	O.O	OOO	OOO	OOO	O.O	OO	OO.O
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Figure 1. System and registry. (A) Schematic representation of the system platform from monitoring to storage. (B) Representative image of the bedside equipment.
AC, anticoagulants; BFR, blood flow rate; CONTINUAL, Continuous mOnitoriNg viTal sIgN dUring hemodiALysis; ECG, electrocardiogram; HD, hemodialysis; HIS, hospital information system; HR, heart rate; SpO_2, peripheral oxygen saturation; Temp, temperature; UF, ultrafiltration.

sentative image of the bedside system equipment which provided time-synchronized data to facilitate integrated biosignal analysis. Data recording was initiated once the connection between the monitors and the Vital Recorder was established. The connection started to work when the HR and SpO_2 input values were recorded more than 5 times within 1 minute. The data were continuously backed up to the intranet-attached storage. The recordings and transfers automatically ended after 10 minutes if the biosignal inputs stopped. Subsequently, clinicians could monitor the real-time biosignals via the screen of any accessible computer. After acquiring the hemodialysis and biosignal data, these were merged based on unique identifiers such as date, time, and the bed number for the hemodialysis session.

Safety issue

The research team regularly inspects the system and the registry every month.

Statistical analysis

All statistical analyses were performed using IBM SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Data are presented as percentages for categorical parameters. Means ± standard deviations or medians (interquartile ranges) were used for continuous parameters according to the normal distribution.

Results

Baseline characteristics during the initial 8-month period

Data were collected for cases during an initial 8-month period and data for approximately 300 sessions per month continue to be collected. A total of 2,243 hemodialysis sessions were collected from 612 patients between September 2020 and April 2021. The mean age was 64 ± 15 years old, and 1,279 (57.0%) were male. Comorbidities of permanent and paroxysmal atrial fibrillation were noted in 11.4% and 5.8% of cases, respectively. The hemodialysis time per session was 3.7 ± 0.9 hours. The initial blood flow rate and target ultrafiltration were 220 ± 38 mL/min and 1.7 ± 1.0 L, respectively. More than 60% of patients used nafamostat mesylate as an anticoagulant. Additional information is presented in Table 1.

Hemodynamic complications

Four representative cases with hemodynamic complications are presented to support the need for continuous monitoring of biosignals, and the present system and relevant registry are proposed as an approach to address this unmet need.

The first case was an 80-year-old male patient who was admitted due to aspiration pneumonia. He had been on hemodialysis for 6 years due to diabetic nephropathy. His comorbidities included hypertension, immune thrombocy-

Table 1. Baseline characteristics of the hemodialysis sessions

Variable	Total
No. of patients	2,243
Age (yr)	64.1 ± 14.6
Male sex	1,279 (57.0)
Body mass index (kg/m^2)	23.7 ± 6.2
Comorbidity	
Hypertension	2,166 (96.6)
Diabetes mellitus	1,770 (78.9)
Heart failure	361 (16.1)
Coronary artery disease	599 (26.7)
Stroke	354 (15.8)
Permanent atrial fibrillation	256 (11.4)
Paroxysmal atrial fibrillation	130 (5.8)
Hemodialysis time (hr)	4.0 (3.5–4.0)
Blood flow rate (mL/min)	219.9 ± 37.6
Ultrafiltration (L)	1.7 ± 1.0
Dialysate findings	
Dialysate sodium (mmol/L)	137.8 ± 1.6
Dialysate potassium (mmol/L)	2.3 ± 0.6
Dialysate bicarbonate (mmol/L)	33.7 ± 1.4
Dialysate temperature (°C)	36.5 ± 0.6
Use of anticoagulant	
Heparin	713 (31.8)
Nafamostat mesilate	1,357 (60.5)
None	173 (7.7)
Access	
Arteriovenous fistula	1,072 (47.8)
Arteriovenous graft	128 (5.7)
Catheter	1,043 (46.5)

Data are expressed as number only, mean ± standard deviation, or number (%).

topenia, and two-vessel coronary artery disease. The initial systolic and diastolic BPs were 175 mmHg and 72 mmHg, respectively, with an HR of 81 per minute. He had a normal sinus ECG rhythm. After starting hemodialysis, his BP gradually decreased to 130/56 mmHg at 34 minutes and 98/54 mmHg at 97 minutes. The patient reported no symptoms, and BP then increased up to 176/72 mmHg at 130 minutes without prompting any medical action (Fig. 2). The National Kidney Foundation's Kidney Disease Outcomes Quality Initiative guidelines define intradialytic hypotension as a decrease in either systolic BP of ≥20 mmHg or mean arterial pressure of ≥10 mmHg [19]. This case is a clear example of intradialytic hypotension, but physicians were not notified because his BP recovered. Nevertheless, recurrent hypotensive events, even without symptoms and with recovery, could be associated with a high risk of cardiovascular death and thus should be continuously monitored.

The second case was a 52-year-old male patient who received a kidney transplant because of progressive immunoglobulin A nephropathy and underwent radical nephrectomy of the graft 10 years later because of kidney cancer. Accordingly, the patient underwent hemodialysis thrice weekly for 7 years. His comorbidities included hypertension, hypothyroidism, and left ventricular hypertrophy. On initiation of hemodialysis, sinus tachycardia was noted, and the systolic and diastolic BPs were 156 mmHg and 120 mmHg, respectively. Forty-six minutes after starting hemodialysis, the ratio of R to S on ECG was ≥1 [20], followed by depression of the ST segment and high amplitude of the R wave (Fig. 3). His BP increased over time, but he did not have any symptoms, such as chest pain or dyspnea. This case indicates that the system could be used to identify subclinical cardiac ischemia.

The third case was a 66-year-old female patient who had been on hemodialysis for 9 years because of drug-induced nephrotoxicity. Her comorbidities included hypertension and paroxysmal atrial fibrillation. She was admitted to the ward because of fungal pneumonia. Before hemodialysis, she had a normal sinus ECG rhythm, and HR was 98 beats per minute. The initial systolic and diastolic BP values were 140 mmHg and 82 mmHg, respectively. Paroxysmal atrial fibrillation occurred at 60 minutes, followed by a drop in systolic and diastolic BPs to 90 mmHg and 63 mmHg, respectively (Fig. 4). This case indicates that a preceding arrhythmia during hemodialysis can affect the risk of hypotension.

The fourth case was a 68-year-old female patient. She was on hemodialysis for 7 years due to diabetic nephropathy. Her comorbidities included hypertension, paroxysmal atrial fibrillation, and three-vessel coronary artery disease. She

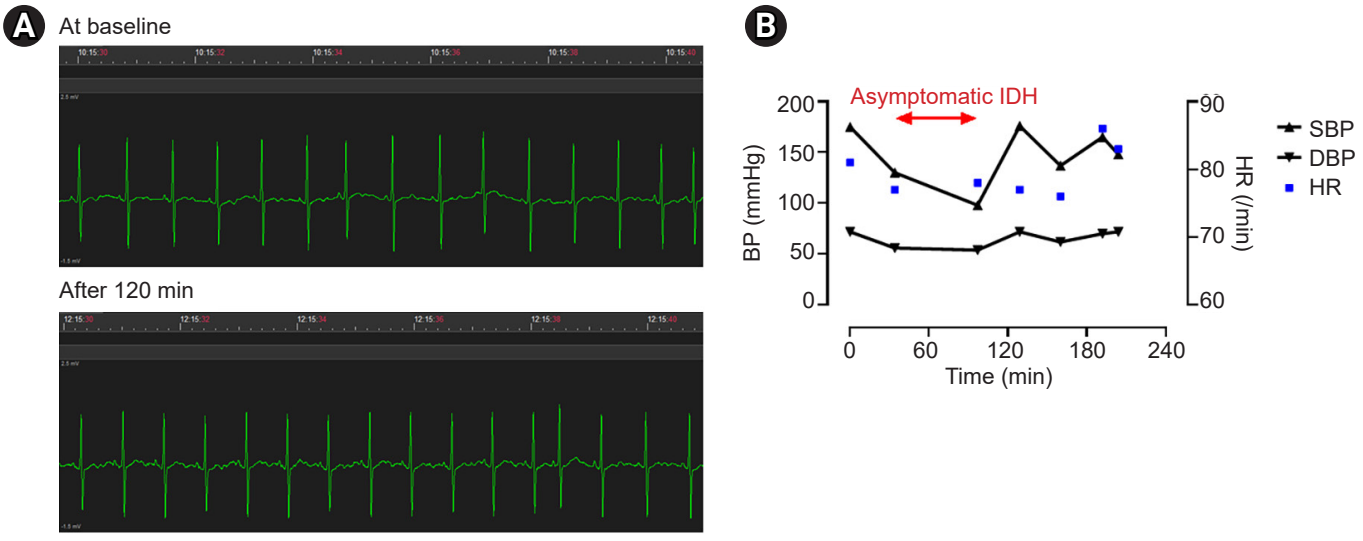


Figure 2. Case with subclinical intradialytic hypotension (IDH). (A) Biosignal changes with time of dialysis as monitored through the system. Sweep rate = 25 mm/sec. Voltage (vertical axis) against time (horizontal axis) = −1.5 to 2.5 mV. (B) Blood pressure (BP) and heart rate (HR) during hemodialysis.
DBP, diastolic BP; SBP, systolic BP.

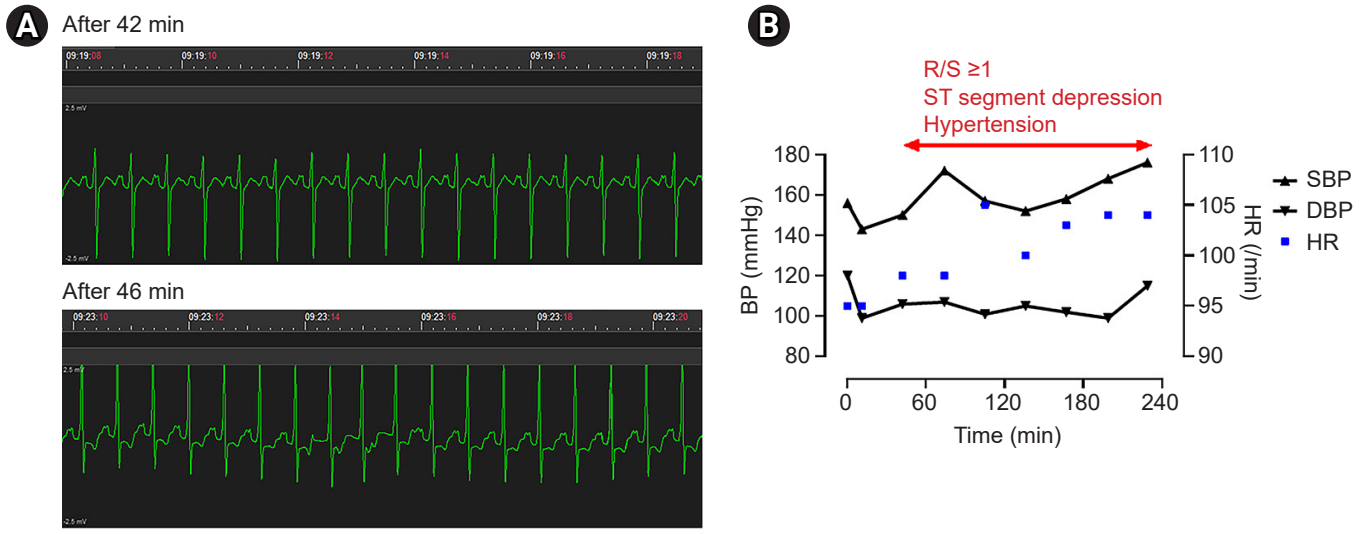


Figure 3. Case with intradialytic hypertension. (A) Biosignal changes with time of dialysis as monitored through the system. Sweep rate = 25 mm/sec. Voltage (vertical axis) against time (horizontal axis) = −2.5 to 2.5 mV. (B) Blood pressure (BP) and heart rate (HR) during hemodialysis. An R/S ratio equal to or greater than 1 suggests the presence of potential pathology in heart.
DBP, diastolic BP; SBP, systolic BP.

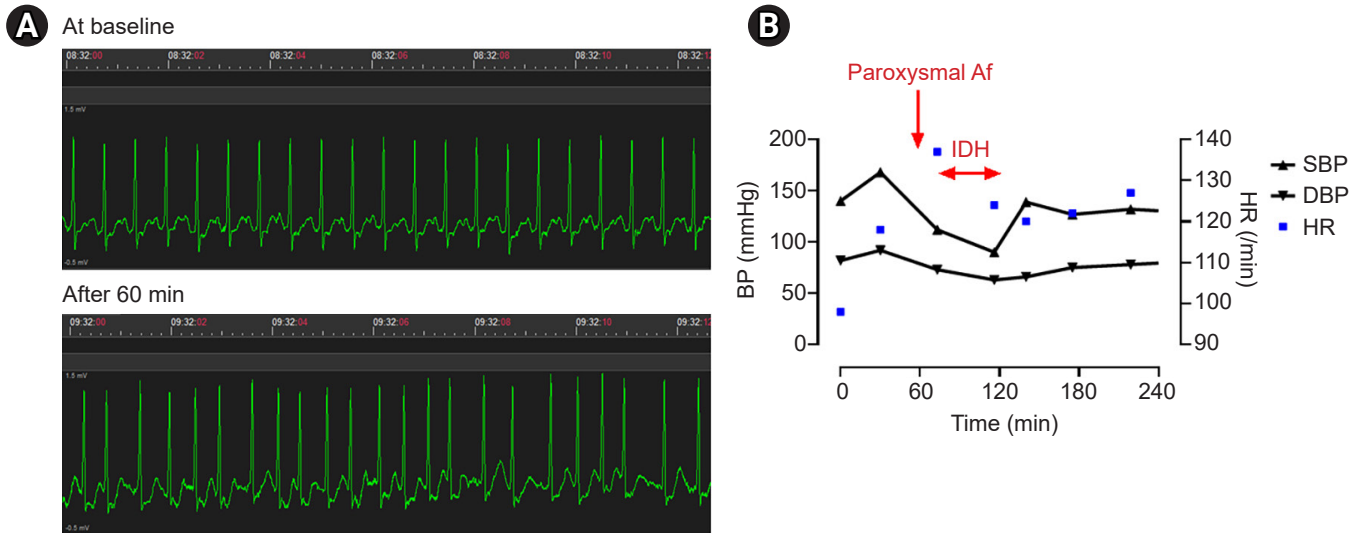


Figure 4. Case with paroxysmal atrial fibrillation (Af), followed by intradialytic hypotension (IDH). (A) Biosignal changes with time of dialysis as monitored through the system. Sweep rate = 25 mm/sec. Voltage (vertical axis) against time (horizontal axis) = −0.5 to 1.5 mV. (B) Blood pressure (BP) and heart rate (HR) during hemodialysis.
DBP, diastolic BP; SBP, systolic BP.

had received a percutaneous coronary artery intervention procedure on the proximal, middle left anterior descending, and right coronary arteries 3 years before. She was admitted due to left foot necrosis and underwent an amputation below the knee. At 60 minutes after starting hemodialysis, she had nonsustained ventricular tachycardia (Fig. 5) for her ECG rhythm, and this arrhythmia was repeated in subsequent hemodialysis sessions. Currently, limited data for the prognostic significance of incidentally detected arrhythmias in hemodialysis patients are limited. Therefore, monitoring intradialytic arrhythmia may be helpful for identifying patients at risk of sudden complications.

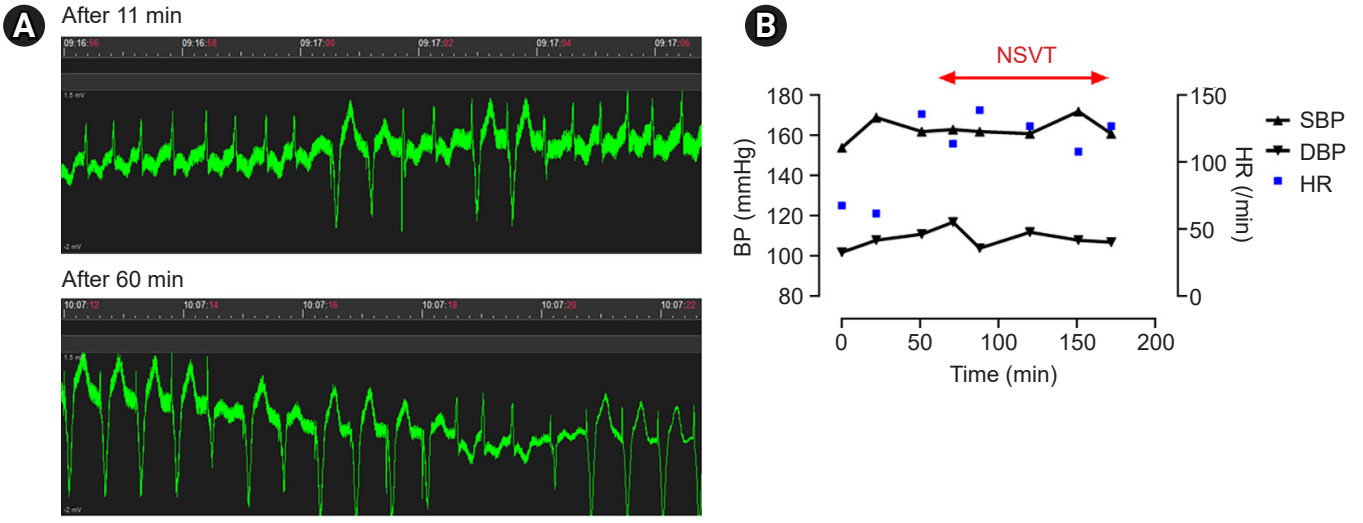


Figure 5. Case with intradialytic nonsustained ventricular tachycardia (NSVT). (A) Biosignal changes with time of dialysis as monitored through the system. Sweep rate = 25 mm/sec. Voltage (vertical axis) against time (horizontal axis) = –2.0 to 1.5 mV. (B) Blood pressure (BP) and heart rate (HR) during hemodialysis.
SBP, systolic BP; DBP, diastolic BP.

Discussion

Biosignal monitoring may be essential for detecting and preventing intradialytic complications. We developed an intradialytic biosignal-integrating system, which continuously updated the CONTINUAL registry. This approach can overcome some inherent limitations of current technology, such as providing real-time monitoring and storage of data. In this report, we also provided representative cases with hemodynamic complications, all of which required prompt prediction, prevention, and treatment. This CONTINUAL registry will be used in the future for predicting patient risks and preventive hemodialysis services based on both handcrafted and artificial intelligence models.

An approach that supports continuous and real-time monitoring of biosignals during hemodialysis is needed, and it will be more feasible if the system is noninvasive. This will allow clinicians to dynamically track changes in the patient statuses during hemodialysis more closely than with sporadic measurements conducted at most centers [21]. As shown in previous cases, a threshold number of sessions could provide sufficient data to predict hemodynamic complications during hemodialysis, some of which can have asymptomatic features. Hemodialysis can induce significant alterations in the hemodynamics of the circulatory system, which imposes a cardiac burden [22]. The burden will manifest as arrhythmias, silent or evident myocardial ischemia, and reversible or irreversible cardiac dysfunction [23]. Currently, hemodialysis machines do not collect biosignal datasets, and thus, some biosignals are missed. This missing data may reflect the cardiovascular risk of hemodialysis patients.

The practical goal of using this system is to utilize the biosignal registry for developing predictive models and to enhance decisions for complication risks. The large quantity of biosignals necessitates advanced or novel analytics that range from collection to interpretation [24]. Machine learning, including deep learning, is a rapidly developing branch of artificial intelligence that has shown promise for use in clinics [13,25]. A major limitation in utilizing biosignals for artificial intelligence-based clinical purposes is the lack of data storage [26]. This system supports intranet-attached storage to facilitate future utilization. The availability of a large, readily accessible registry with biosignals can shorten the time of model training [26]. We are currently conducting several projects with the help of machine learning using this CONTINUAL system.

Some limitations should be considered before fully utilizing this system and registry. The connection with the bedside monitor could be momentarily lost because of vio-

lent movement or arbitrary removal of the connector. This may result in loss of the significant biosignals and relevant intradialytic events and thus provide insufficient information to medical doctors or in developing models. The registry currently consists of data from hemodialysis patients hospitalized in a tertiary hospital, whose characteristics and risks of hemodynamic complications could differ from those admitted to general hospitals.

In summary, we developed an integrated system of intradialytic biosignals that included BP, HR ECG, and photoplethysmogram with SpO_2. This system-derived biosignal registry will facilitate epidemiological surveys on hemodynamic complications, enhance artificial intelligence models for predicting risks, and thus improve patient outcomes.

Conflicts of interest

All authors have no conflicts of interest to declare.

Authors' contributions

Conceptualization: SSH
Data curation: S Kim, DY, HCL, CWJ
Formal analysis: S Kim, DY, S Kwon, SRL, KK
Investigation: S Kim, DY, S Kwon, SRL, KK, YCK, DKK, KHO, KWJ, YSK
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References

1. Liyanage T, Ninomiya T, Jha V, et al. Worldwide access to treatment for end-stage kidney disease: a systematic review. *Lancet* 2015;385:1975–1982.
2. Saran R, Robinson B, Abbott KC, et al. US Renal Data System 2018 annual data report: epidemiology of kidney disease in the United States. *Am J Kidney Dis* 2019;73(3 Suppl 1):A7–A8.
3. Himmelfarb J, Vanholder R, Mehrotra R, Tonelli M. The current and future landscape of dialysis. *Nat Rev Nephrol* 2020;16:573–585.
4. Davenport A. Intradialytic complications during hemodialysis. *Hemodial Int* 2006;10:162–167.
5. Ritz E, Bommer J. Cardiovascular problems on hemodialysis: current deficits and potential improvement. *Clin J Am Soc Nephrol* 2009;4 Suppl 1:S71–S78.
6. Ortiz A, Covic A, Fliser D, et al. Epidemiology, contributors to, and clinical trials of mortality risk in chronic kidney failure. *Lancet* 2014;383:1831–1843.
7. Collins AJ, Foley RN, Gilbertson DT, Chen SC. United States Renal Data System public health surveillance of chronic kidney disease and end-stage renal disease. *Kidney Int Suppl (2011)* 2015;5:2–7.
8. Charytan DM, Foley R, McCullough PA, et al. Arrhythmia and sudden death in hemodialysis patients: protocol and baseline characteristics of the monitoring in dialysis study. *Clin J Am Soc Nephrol* 2016;11:721–734.
9. Yoon D, Lee S, Kim TY, Ko J, Chung WY, Park RW. System for collecting biosignal data from multiple patient monitoring systems. *Healthc Inform Res* 2017;23:333–337.
10. Krittanawong C, Rogers AJ, Johnson KW, et al. Integration of novel monitoring devices with machine learning technology for scalable cardiovascular management. *Nat Rev Cardiol* 2021;18:75–91.
11. Palmieri F, Gomis P, Ferreira D, et al. Monitoring blood potassium concentration in hemodialysis patients by quantifying T-wave morphology dynamics. *Sci Rep* 2021;11:3883.
12. Burkert A, Scholze A, Tepel M. Noninvasive continuous monitoring of digital pulse waves during hemodialysis. *ASAIO J* 2006;52:174–179.
13. Lee H, Yun D, Yoo J, et al. Deep learning model for real-time prediction of intradialytic hypotension. *Clin J Am Soc Nephrol* 2021;16:396–406.
14. Roy-Chaudhury P, Tumlin JA, Koplan BA, et al. Primary outcomes of the Monitoring in Dialysis Study indicate that clinically

significant arrhythmias are common in hemodialysis patients and related to dialytic cycle. *Kidney Int* 2018;93:941–951.
15. Mc Causland FR, Tumlin JA, Roy-Chaudhury P, et al. Intradialytic hypotension and cardiac arrhythmias in patients undergoing maintenance hemodialysis: results from the Monitoring in Dialysis Study. *Clin J Am Soc Nephrol* 2020;15:805–812.
16. Verde E, Pérez de Prado A, López-Gómez JM, et al. Asymptomatic intradialytic supraventricular arrhythmias and adverse outcomes in patients on hemodialysis. *Clin J Am Soc Nephrol* 2016;11:2210–2217.
17. Rogovoy NM, Howell SJ, Lee TL, et al. Hemodialysis procedure-associated autonomic imbalance and cardiac arrhythmias: insights from continuous 14-day ECG monitoring. *J Am Heart Assoc* 2019;8:e013748.
18. Lee HC, Jung CW. Vital Recorder: a free research tool for automatic recording of high-resolution time-synchronised physiological data from multiple anaesthesia devices. *Sci Rep* 2018;8:1527.
19. K/DOQI Workgroup. K/DOQI clinical practice guidelines for cardiovascular disease in dialysis patients. *Am J Kidney Dis* 2005;45(4 Suppl 3):S1–153.
20. Coşkun A, Eren SH. R/S ratio in lead II, and the prognostic significance of red cell distribution width in acute coronary syndrome. *World J Clin Cases* 2019;7:2217–2226.
21. Sun Y, Guo F, Kaffashi F, Jacono FJ, DeGeorgia M, Loparo KA. INSMA: an integrated system for multimodal data acquisition and analysis in the intensive care unit. *J Biomed Inform* 2020;106:103434.
22. Cozzolino M, Galassi A, Pivari F, Ciceri P, Conte F. The cardiovascular burden in end-stage renal disease. *Contrib Nephrol* 2017;191:44–57.
23. Zuidema MY, Dellsperger KC. Myocardial stunning with hemodialysis: clinical challenges of the cardiorenal patient. *Cardiorenal Med* 2012;2:125–133.
24. Obermeyer Z, Emanuel EJ. Predicting the future: big data, machine learning, and clinical medicine. *N Engl J Med* 2016;375:1216–1219.
25. Chen JB, Wu KC, Moi SH, Chuang LY, Yang CH. Deep learning for intradialytic hypotension prediction in hemodialysis patients. *IEEE Access* 2020;8:82382–82390.
26. Goodwin AJ, Eytan D, Greer RW, et al. A practical approach to storage and retrieval of high-frequency physiological signals. *Physiol Meas* 2020;41:035008.