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Design and Evaluation of an Abdominal Voice Wearable System for Mitigating Hemodialysis-Related Complications in End-Stage Renal Disease Patients

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Abstract **-** End-stage renal disease (ESRD) patients often face complications during hemodialysis, such as hypotension and gastrointestinal disorders. Still, traditional monitoring methods cannot capture patients' dynamic physiological changes in real time. To address this problem, this study focuses on the design and evaluation of a wearable abdominal sound system with a human-computer interface: the device can detect and analyze physiological signals such as bowel peristalsis in real-time, and at the same time, through multimodal data processing and visualization interface, provide personalized health management advice to healthcare teams and patients. Based on this system, we further propose a cross-disciplinary model that integrates dietary management and health monitoring, not only to reduce the risk of complications during hemodialysis but also to improve patients' awareness of their condition and quality of life. Overall, this study focuses on the potential value of human-computer interaction technology in clinical monitoring and patient self-management and explores how wearable devices can enhance patient engagement and compliance through real-time feedback and user-friendly interfaces.

Keywords**:** end-stage renal disease, hemodialysis, abdominal voice wearable device, bowel sound monitoring, hypotension, gastrointestinal complications

1. Introduction

End-Stage Renal Disease (ESRD) patients undergoing hemodialysis often face fluid balance disorders, electrolyte imbalances, and gastrointestinal abnormalities, with intradialytic hypotension and gastrointestinal disturbances being the most prevalent complications. These issues not only compromise treatment efficacy but also reduce the overall quality of life. Currently, routine hemodialysis monitoring relies heavily on conventional instruments and clinical observation, making it challenging to provide timely, dynamic, and patient-specific physiological assessments [1].

Recent advances in wearable technology and smart health monitoring offer new opportunities for real-time, personalized care. This study focuses on a bowel sound detection device that leverages highly sensitive microphones and sensors to capture intestinal motility patterns and then delivers immediate physiological feedback and individualized recommendations through an intuitive user interface. By integrating these sensor data with dietary guidance and health monitoring, we propose a novel human-wearable interaction model aimed at reducing complications during hemodialysis. This model empowers both patients and healthcare providers by offering real-time alerts, data visualization, and personalized support to enhance physiological stability, improve cognitive function, and ultimately elevate patients' quality of life [2].

2. Related work

Bowel sounds (BS) have been identified as key clinical indicators of intestinal health, providing essential insights into bowel function and patient recovery status [3]. In response, we propose an abdominal sound wearable device that seamlessly integrates bowel sound monitoring, data analysis, and real-time feedback through a highly sensitive microphone and a multi-sensor array. The device is non-invasive and designed to fit snugly on the abdomen, capturing diverse physiological signals simultaneously. By precisely positioning and calibrating the sensors, we can detect subtle yet complex bowel sounds, thereby enhancing our understanding of gastric and intestinal activity [4].

To interpret these signals, we employ advanced techniques such as the Short-Time Fourier Transform (STFT), which converts the time-frequency characteristics of bowel sounds into quantifiable and easily interpretable physiological markers [5]. Machine learning–based analytical models further enable the recognition of both normal and abnormal bowel sound patterns, gradually establishing a personalized baseline for each user [6]. As more data is gathered over time, these models adapt dynamically to varying patient profiles and disease states, making diagnoses and decision-making increasingly accurate and robust.

A key feature of this system is its real-time interaction with both clinicians and patients. We have developed a mobile application and a user-friendly visualization interface to deliver analysis results in the most accessible form. Alert mechanisms are triggered at the earliest sign of any abnormal signal, empowering clinicians and patients to respond promptly with tailored interventions or treatment adjustments. This rapid, data-driven feedback loop not only promotes more effective clinical practice but also encourages patients to actively participate in their own healthcare decisions.

By continuously tracking bowel sounds, our wearable device can help identify potential risks of complications—particularly in long-term treatment monitoring scenarios such as hemodialysis for end-stage renal disease patients—and provide timely dietary and hygienic recommendations. This integrated approach supports clinical decision-making while fostering a patient-centered experience, thus paving the way for the next generation of personalized, intelligent health monitoring.

3. Materials and Methods

By continuously tracking bowel sounds, our wearable device can help identify potential risks of complications—particularly in long-term treatment monitoring scenarios such as hemodialysis for end-stage renal disease patients—and provide timely dietary and hygienic recommendations. This integrated approach supports clinical decision-making while fostering a patient-centered experience, thus paving the way for the next generation of personalized, intelligent health monitoring.

In this study, a custom-designed contact microphone for physiological monitoring was developed and produced in limited quantities. The core sensor integrates an electromagnetic (copper-foil) element and a piezoelectric transducer optimized for low harmonic frequencies (1.3 kHz), encapsulated within a thin (~1 cm) 3D-printed enclosure. This enclosure includes a standardized stethoscope membrane, fabricated from epoxy resin and fiberglass, for reliable sound transmission. A notch on the outer shell allows for convenient charging access, while the skin-contact surface—constructed from medical-grade silicone—enables high-fidelity audio capture at 24-bit depth, covering a wide dynamic range from faint bowel sounds to louder single-event signals.

In practical use, participants are instructed to place the microphone on the mid-abdominal area (Fig. 1) and activate a companion mobile application to record audio samples. The system then correlates user-selected parameters with automatically quantified bowel function data. To enhance signal clarity, potential disruptions such as speech and environmental noise are actively minimized throughout the recording process, thereby ensuring more accurate and meaningful physiological measurements.

Fig. 1: Wearable Device Schematic.

Table 1: Baseline description and comparison

Factor	Classification	Yes (n = 25)	No (n = 25)	Chi2/t	*P*
Gender, n(%)	Male	4 (16.0%)	4 (16.0%)		
	Female	21 (84.0%)	21 (84.0%)		
Age (year)	(m ± sd)	61.6 ± 11.0	64.0 ± 11.7	1.23	0.2188
HD sessions		36	36		
Pre-SBP (mmHg)	(m ± sd)	144.5 ± 14.9	133.5 ± 23.8	2.97	0.0042
Pre-DBP (mmHg)	(m ± sd)	80.3 ± 8.7	75.6 ± 12.1	2.46	0.0165
BMI (Kg/m2)	(m ± sd)	21.9 ± 3.3	21.6 ± 2.8	0.51	0.6097
IDWG%	(m ± sd)	3.5 ± 1.3	3.9 ± 1.0	1.77	0.0800
uf (L)	(m ± sd)	2.3 ± 0.9	2.4 ± 0.7	0.72	0.4755
Kt/V	(m ± sd)	1.3 ± 0.3	1.4 ± 0.3	1.09	0.2777

Abbreviations: ESRD = end-stage renal disease, idwg = interdialysis weight gain, uf = average reality ultrafiltration volume, BMI = body mass index, Pre-SBP = predialysis Systolic Blood Pressure, Pre-DBP = predialysis Diastolic Blood Pressure, Kt/V: Urea clearance index

This study examined dialysis patients who used the Abdominal Sound Device (AbSound) compared to those who did not. A total of 50 patients were divided equally into two groups of 25: the "Yes" group (device use) and the "No" group (no device use). Both groups had the same gender distribution (16% male, 84% female) with no statistical difference. The mean age in the Yes group was 61.6 years, slightly lower than 64.0 years in the No group, although this difference was not significant (p = 0.2188).

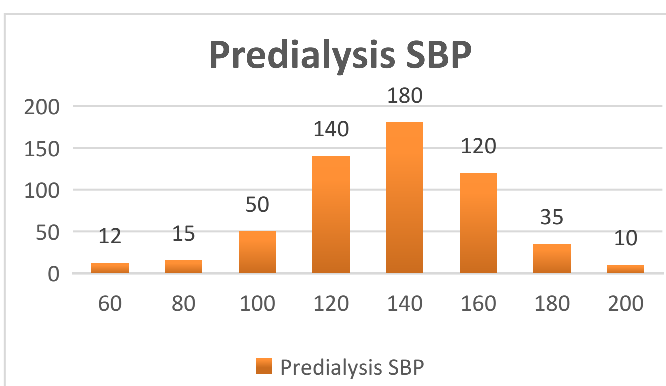

Fig. 2: Predialysis Patient's SBP

Each group received 36 dialysis sessions per week. The Yes group showed a marginally lower inter-dialysis weight gain percentage (IDWG%) than the No group (3.5% vs. 3.9%), approaching but not reaching significance ($p = 0.0800$). Notably, pre-dialysis systolic (144.5 mmHg) and diastolic (80.3 mmHg) blood pressures were significantly higher in the Yes group compared to the No group (133.5 mmHg systolic and 75.6 mmHg diastolic, $p = 0.0042$ and $p = 0.0165$, respectively). By contrast, ultrafiltration volume (uf), dialysis efficiency (Kt/V), and body mass index (BMI) did not differ significantly between the two groups.

This research protocol was approved by the Medical Ethics Committee of the National Defense Medical Center, Taiwan (IRB No. KY2021-609).

4. Using the template results

4.1. Preventing Dialysis-Related Hypotension

This study highlights the use of an abdominal voice wearable device in hemodialysis to offer real-time monitoring and analysis of bowel sounds, ultimately providing an objective basis for clinical decision-making. The core value of this technology is its potential to enhance fluid balance management, support personalized dietary recommendations, and enable early detection and intervention for gastrointestinal complications.

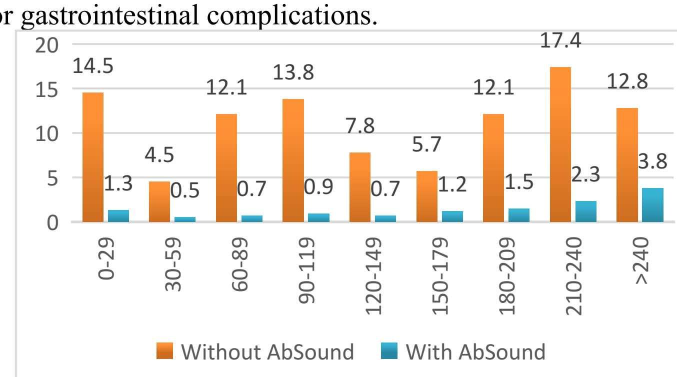

Fig. 3: Time into HD sessions(min)

In the context of preventing dialysis-related hypotension, the device relies on highly sensitive microphones and sensors to continuously track peristaltic frequency and characteristics—physiological indicators closely linked to fluid movement in the body. When abnormal bowel sound patterns arise during the fluid removal phase, these readings can signal reduced tolerance for ultrafiltration, prompting clinicians to adjust dialysis parameters proactively to avoid overhydration. This approach reduces hypotensive events. Furthermore, any significant decrease in bowel sound activity during dialysis triggers an immediate alert, prompting an assessment of the patient's hemodynamic status and timely interventions to ensure both safety and comfort.

4.2. Mechanism of Cognitive Enhancement

Another focus of this study is the maintenance of neurocognitive function in hemodialysis patients through an integrated care strategy that aligns intestinal physiology, cerebral perfusion, and mental health. Dialysis-associated hypotension poses a major clinical challenge; when blood pressure becomes unstable, cerebral perfusion diminishes, risking cognitive deficits and possible long-term neurological damage. Consequently, clinicians must precisely regulate the dialysis rate and fluid removal to maintain a stable hemodynamic state. A more consistent perfusion not only helps avert confusion, dizziness, and more serious neurological issues but also indirectly preserves the patient's cognitive function.

4.3. Optimizing Dietary Management

Beyond mitigating hypotension, long-term data gathered by the abdominal voice device can serve as a basis for personalized dietary planning. Because electrolyte balance in dialysis patients is strongly linked to gastrointestinal function, analyzing bowel sounds before and after dialysis can guide dietitians and healthcare professionals in refining dietary advice. For instance, identifying that a patient experiences gastrointestinal discomfort during dialysis may prompt recommendations to avoid high-sodium or high-potassium foods beforehand, thereby minimizing electrolyte imbalances. At the same time, encouraging high-fiber intake and controlling meal sizes can promote intestinal motility, bolster gastrointestinal stability, and ultimately enhance overall quality of life.

4.4. Early Detection and Intervention of Gastrointestinal Complications

Addressing gastrointestinal complications is another key advantage of this wearable technology. When bowel sound fluctuations suggest emerging pathologies such as reduced bowel motility or impending obstruction, the device's feedback system alerts clinicians to implement timely adjustments—ranging from modifying dialysis parameters to altering medications or diets. Early intervention of this sort can mitigate the severity of complications, thereby promoting smoother patient recovery, improving clinical resource utilization, and reducing healthcare costs.

In sum, the integration of an abdominal voice wearable device into hemodialysis treatment offers a novel and valuable approach. Providing real-time fluid balance monitoring and alerts for abnormal conditions, helps curtail dialysis-related hypotension. Meanwhile, the longitudinal collection and analysis of bowel sound data enable personalized dietary guidance and facilitate swift interventions upon early detection of gastrointestinal complications. Taken together, this clinical application not only improves the safety and stability of the dialysis process but also lays a robust foundation for advancing personalized medicine and elevating the overall quality of care.

5. Discussion

5.1. Exact Mechanism of Hypotension Reduction

The primary goal of this study is to establish a multifaceted management framework that uses an abdominal voice wearable device to deliver real-time monitoring and analysis, thereby addressing the hemodynamic instability and comorbid risks frequently observed in hemodialysis patients. Foremost in this framework is fluid dynamics monitoring. By continuously tracking the acoustic signatures of intestinal motility, the device provides indirect indicators of how fluids are distributed and moving within the patient's body. Equipped with these data, the clinical team can dynamically adjust dialysis parameters, mitigating the likelihood of over-dehydration and its associated hypotensive events. This real-time, personalized fluid removal strategy renders hemodialysis more precise and stable (Fig. 4).

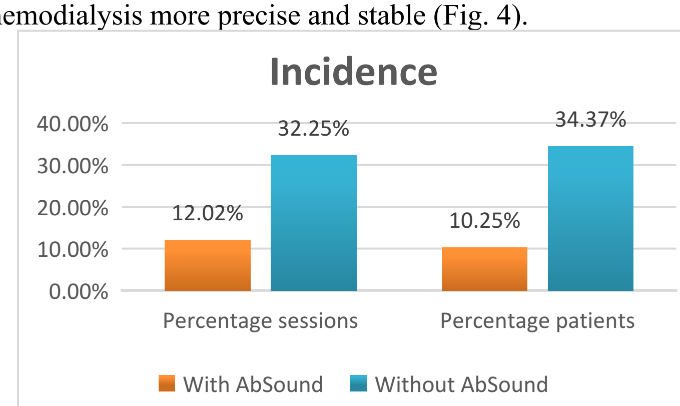

Fig. 4: Comparison of the incidence of using AbSound.

In addition to optimizing fluid balance, bowel sound monitoring offers an indirect window into autonomic function—particularly the interplay between sympathetic and parasympathetic activity, which is crucial for maintaining stable blood pressure. When the abdominal sound data indicate atypical neuromodulatory shifts during dialysis, clinicians are alerted to the potential for circulatory imbalances. Dialysis protocols or supplementary interventions can then be proactively modified to prevent hypotension, empowering the clinical care team to take early, targeted action.

Beyond immediate clinical decision-making, long-term analysis of bowel sound data facilitates customized nutrition and fluid intake management. Because many hemodialysis patients must rigorously monitor sodium, potassium, and protein intake, observing trends in bowel sound activity over time—correlated with individual dietary patterns—enables more finely tuned dietary regimens. By preemptively reducing the impact of high-risk foods on electrolytes and hemodynamics before, during, and after dialysis, patients can maintain stronger physiologic stability throughout the treatment cycle.

Taken together, these three core functions—fluid dynamics monitoring, autonomic regulation insights, and targeted nutritional interventions—position the Abdominal Voice Device as a real-time, user-centric clinical tool. By integrating these components, the technology expands the scope of hemodialysis management, promising better quality of life and more robust treatment outcomes for patients, and paving the way for further innovation in patient-centered care.

5.2. Mechanism of Cognitive Enhancement

While hemodynamics remains a critical concern for cognitive function in dialysis patients, emerging evidence underscores the significance of the gut-brain axis. Factors such as dysbiosis, poor bowel motility, and heightened inflammation can influence central nervous system function through neurological, immune, and hormonal pathways. By capturing bowel sound variations in real time, clinicians can detect early signs of such imbalances and tailor dietary adjustments to help curb the growth of harmful gut microorganisms and minimize inflammatory triggers. Consequently, stabilizing neurotransmitter balances in the brain can help sustain or improve cognitive performance.

Another vital aspect involves the psychological burden of long, repetitive dialysis sessions. Anxiety and uncertainty can undermine memory and concentration, creating a feedback loop of mental stress and physiological deregulation. In response, this study incorporates immediate feedback features paired with structured medical and educational interventions. Through intuitive visual or auditory prompts, patients gain a clearer understanding of their real-time condition, receive timely reassurance, and become more engaged in self-care practices. This positive engagement not only reduces emotional strain but also preserves cognitive resilience.

Bringing these elements together, we propose a comprehensive care model focused on stabilizing cerebral perfusion, modulating gut-brain dynamics, and alleviating psychological stress. This integrated approach—anchored by advanced physiological signal monitoring, precise dietary control, and real-time patient-clinician feedback—provides robust evidence-based guidance for clinical practice while opening new avenues for future research into gut-brain interactions and personalized therapeutic strategies.

5.3. Benefit Assessment in Clinical Practice

By cross-analyzing clinical data, this study demonstrates that dialysis patients utilizing the abdominal voice wearable device experience a marked reduction in both hypotensive events and gastrointestinal complications. Additionally, fusing multiple parameters—including bowel sounds, blood pressure, and heart rate—enhances the predictive accuracy for potential dialysis-related complications.

To quantify the overall impact on quality of life (QoL), we compared QoL scores for patients who used the AbSound device against those who did not. The results reveal that individuals without AbSound not only had poorer QoL in dimensions related to kidney disease symptoms and discomfort but also experienced a more pronounced impact on their daily lives. The details, as outlined in Table 2, underscore the device's potential for improving well-being in this patient population.

In conclusion, the abdominal voice wearable device represents a transformative step forward in hemodialysis care. By offering a user-centered, real-time monitoring system that integrates fluid management, autonomic function insights, and tailored dietary approaches—along with a comprehensive strategy for supporting cognitive health—this technology helps reduce adverse events, elevates patient engagement, and opens new horizons for personalized medicine in renal care.

Table 2: Overall difference in QOL between patients with or without Absound

Overall test	**Overall test**	F value	P value

Mental health	Group (With or without frequent IDH) $_a$	0.25	0.6435
Physiological health	Group (With or without frequent IDH) $_a$	5.69	0.0185
Burden kidney disease brings on life	Group (With or without frequent IDH) $_a$	0.66	0.5665
Symptoms and discomfort of kidney disease	Group (With or without frequent IDH) $_a$	8.14	0.0046
Impact of kidney disease on life	Group (With or without frequent IDH) $_a$	7.83	0.0079

6. Conclusion

This study demonstrates that the abdominal voice wearable device can significantly reduce both hyponatremia and gastrointestinal complications in end-stage renal disease (ESRD) patients undergoing hemodialysis. Moreover, by providing real-time monitoring and personalized recommendations, the device not only enhances patients' quality of life but also supports cognitive function.

Looking ahead, the integration of bowel sound monitoring with multiple physiological signals—such as blood pressure, blood oxygen, electrocardiogram, and body temperature—promises to create a more comprehensive and intelligent health monitoring system. Leveraging artificial intelligence for early prediction and diagnosis of complications will further refine clinical accuracy and expand the scope of personalized care.

In addition, developing user-friendly human-machine interfaces and remote healthcare support systems will empower both medical teams and patients to track physiological parameters over extended periods. Through adaptive algorithms, they can fine-tune dialysis schedules and dietary plans promptly, thereby achieving more precise health management and ushering in a new era of personalized medicine for chronic kidney disease.

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