



Shaping Tomorrow's Nephrology: Insight-Driven Kidney Care

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Real-Time Optimization of Ultrafiltration and Blood Flow Rate in Hemodialysis Using Offline Reinforcement Learning

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Objectives : Intradialytic hypotension (IDH) and overly aggressive ultrafiltration (UF) remain key barriers to safe, individualized hemodialysis. We developed an offline reinforcement learning (RL) agent to recommend real-time adjustments of UF and blood flow rate (BFR) using the HEMOBP dataset.

Methods : We formulated hemodialysis management as an offline Markov decision process with 10-minute decision intervals over a 4-hour horizon. The state included time-series hemodynamic and dialysis machine signals aggregated per bin and static patient/session characteristics. An Implicit Q-Learning (IQL) policy with a recurrent encoder and twin critics was trained to output bounded continuous actions for UF and BFR. Off-policy evaluation (OPE) incorporated weighted importance sampling-based estimators and fitted Q evaluation (FQE). Uncertainty was summarized using 95% confidence intervals (CIs) from the OPE procedures.

Results : The cohort comprised 924 patients with 126,466 hemodialysis sessions, split into train/validation/test sets of 648/92/184 patients and 89,461/12,826/24,179 sessions, respectively. On the test set, the observed IDH incidence under the behavior (clinician) policy was 54.25% (95% CI 51.95–56.25), whereas the IQL policy was estimated to reduce IDH to 46.00% (95% CI 41.94–50.13) (absolute reduction $\approx$ 8.3 percentage points). The gap to dry weight target was comparable between behavior and IQL policies (0.45 kg [0.42–0.49] vs 0.45 kg [0.40–0.51], respectively), with similar mean total UF (2.53 L vs 2.53 L). FQE estimated improved expected return for the IQL policy compared with behavior (–57.55 [–58.43 to –56.67] vs –85.44 [–86.66 to –84.22]), consistent with lower IDH-related penalties.

Conclusions : In offline evaluation on HEMOBP, an IQL-based agent learned clinically plausible UF/BFR control and was estimated to lower IDH risk without compromising dry-weight targeting on the test set. Prospective validation and safety-constrained deployment strategies are warranted before clinical translation.

Tables_1.jpg



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Table 1. Baseline characteristics of the HEMOBP cohort and data splits

Characteristic	Overall	Train	Validation	Test
N (Patients)	924	648	92	184
Total HD Sessions	126466	89461	12826	24179
Age	63.2 ± 13.3	63.5 ± 13.3	60.8 ± 14.1	63.5 ± 13.0
Male (%)	50.4	50.5	50.0	50.5
Diabetes (%)	39.3	38.7	41.3	40.2
Mean HD Duration (hours)	4.0 ± 0.6	4.0 ± 0.7	4.0 ± 0.6	3.9 ± 0.3
Pre-dialysis SBP (mmHg)	144.3 ± 20.9	144.2 ± 20.4	145.5 ± 21.4	144.1 ± 22.3
Pre-dialysis DBP (mmHg)	68.4 ± 17.5	68.1 ± 17.7	68.6 ± 19.7	69.4 ± 15.9
Pre-dialysis MAP (mmHg)	91.7 ± 21.8	91.4 ± 21.9	91.5 ± 24.3	92.7 ± 20.3
Intra-dialytic Mean SBP (mmHg)	141.7 ± 19.7	141.9 ± 19.2	142.8 ± 20.5	140.4 ± 21.1
Intra-dialytic Mean DBP (mmHg)	67.5 ± 17.2	67.3 ± 17.4	68.2 ± 19.0	67.8 ± 15.4
Intra-dialytic Mean MAP (mmHg)	90.2 ± 21.3	90.2 ± 21.5	90.4 ± 23.5	90.3 ± 19.5
Total UF Removed (kg)	2.7 ± 0.9	2.6 ± 0.9	2.6 ± 0.8	2.7 ± 0.9
Pre-Weight (kg)	61.1 ± 13.1	61.2 ± 13.2	60.1 ± 11.9	61.0 ± 13.3
Dry-Weight (kg)	58.5 ± 12.6	58.7 ± 12.8	57.4 ± 11.0	58.3 ± 12.7
Absolute Wt Diff MAE (kg)	0.5 ± 1.4	0.5 ± 1.5	0.6 ± 1.5	0.4 ± 1.0
Mean BFR (mL/min)	220.7 ± 22.4	220.0 ± 21.8	223.8 ± 26.1	221.7 ± 22.4
IDH sessions (%)	52.6	51.6	52.9	56.1

Table 2. Model performance on the test set using off-policy evaluation (OPE) and fitted Q evaluation (FQE)

Metric	Behavior policy	IQL policy
Empirical Monte Carlo Return	-80.80 ± 2.06	-
Effective Sample Size (ESS)	24179.00	2272.58
FQE Estimated Return (MC Proxy)	-85.44 ± 1.22	-57.55 ± 0.88
Weighted IS (WIS)	-80.80	-59.48

Table 3. Comparison of intradialytic hypotension and fluid removal targets on the test set

Outcome / metric	Behavior policy	IQL policy
IDH incidence, % (95% CI)	54.25 [51.95, 56.25]	46.00 [41.94, 50.13]
Gap to dry weight, kg (95% CI)	0.45 [0.42, 0.49]	0.45 [0.40, 0.51]
Total ultrafiltration volume, L	2.53	2.53

Tables_1.jpg



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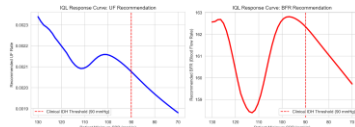
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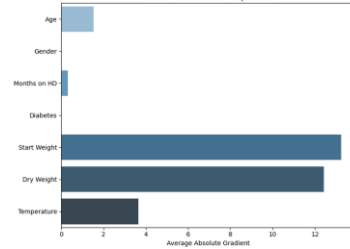
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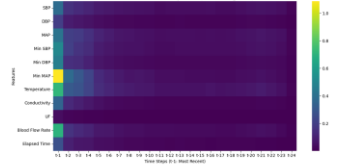
Clinical Sanity Check: Monotonicity Under Dropping Blood Pressure



General: Static Variable Importance



General: Time Series Variable Importance (Gradient Magnitude)



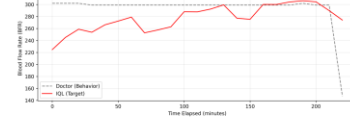
Rank 1 Trajectory (VScore: 5.25) | Start Wt: 68.3kg, Dry Wt: 65.7kg



Machine Intervention - UF Control



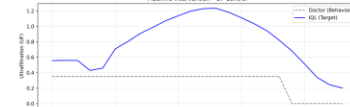
Machine Intervention - Blood Flow Rate (BFR)



Rank 2 Trajectory (VScore: 5.23) | Start Wt: 64.7kg, Dry Wt: 64.0kg



Machine Intervention - UF Control



Machine Intervention - Blood Flow Rate (BFR)

