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Autonomous Human Body Control, Part IX: Blood Urine Nitrogen (BUN) Control during the Dialysis Process using I-First Order, I-Second Order compensators and PD-PI Controller Compared with a PI Controller

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Abstract:

This paper investigates the tuning of PI, PD-PI controllers and I-first order, I-2/2 second compensators from the first and second generation of PID controllers and control compensators to control the BUN (Blood Urine Nitrogen) of a human body during dialysis. The proposed compensators/controllers are tuned using a hybrid approach based on zero/pole cancellation, fulfilling specific characteristics of the proposed control system and a trial and error technique. The BUN process was modeled using pre-published dialysis data and the tuning results of the proposed compensators/controllers are presented and applied to generate the step time response for reference input tracking of a specific level of BUN. The characteristics of the step time responses are compared with those of a conventional PI controller. The best compensators/controller for the control of the human BUN during dialysis is assigned.

***Keywords* — Autonomous human body control, BUN during dialysis, PI controller, I-first order compensator, I-2/2 second order compensator, PD-PI controller, compensator/compensator tuning.**

I. INTRODUCTION

This is the ninth paper of a series of research papers oriented towards the study of autonomous human body control to help reducing the human suffering due to the deficiencies in the operating organs. This paper deals with the control of the blood urine nitrogen (BUN) where it provides important information about the work of the kidneys with normal level of 8 to 24 mg/dL for adult males [1]. Increased BUN levels (> 24 mg/dL for adult males) result in dangerous symptoms on the human health such as: fatigue, weakness, difficulty of concentration, drowsiness, headache, irritability, swollen legs, swelling around eyes, brown urine, reduced urine, loss of appetite, pitching, shortness of breath, kidneys pain and high blood pressure [2]. From here emerges the importance of regulating the BUN to be within the normal range for each age and sex. Unfortunately there a severe shortage in the efforts of regulating the BUN in an automatic way. Here are some of the research efforts regarding the measurement and modeling of the human BUN levels since 2004:

Rao and Prando (2004) tried to answer a question about the methodology suitable to address challenges of the adequacy of dialysis based on urea kinetic modeling. They presented graphical profiles for BUN (in mg/dL) against time (up to 200 hrs.) and different configurations of the dialysis process and the effect of the dialysis parameters on the patient's BUN [3]. August, Parker and Fillippatos et al. (2007) stated that elevated BUN has been linked to poorer outcomes in chronic heart failure. They concluded that BUN measured at hospital admissions was an easy accessible independent predictor of adverse outcomes in acute CHF (congestive Heart Failure) patients [4]. Bechien, Wu, Olaf and Georgios (2011) performed a secondary analysis of three prospective AP cohort studies and adjusted meta-analysis and stratified multivariate logistic regression for age, sex and creatinine levels to determine the risk of mortality associated BUN level at admission and rise in BUN at 24 hrs [5]. Regarding (2015) presented the 2015 update of the Kidney Disease Outcomes Quality Initiative (KDOQI) clinical practice guidelines for hemodialysis adequacy to assist practitioners caring for patients in preparation for and during hemodialysis. He presented new topics including: high frequency, hemodialysis risks, initiation timing, duration and ultrafiltration rate, volume and blood pressure control [6].

Mahdiasanti, Sabarudin and Sulistyarti (2019) described a microfluidic paper-based analysis device for simultaneous quantification of two important biomarkers of kidney function in blood.

They provided a simple disposable portable and inexpenxive colorimetric method for the quantification of blood urea nitrogen (BUN) and serum creatinine. They optimized various experimental parameters to achieve the best performance of their technique [7]. Yang et al. (2021) established a method based on the urea kinetic model named 'assessment method' to calculate BUN after hemodialysis based on parameters obtained during the hemodialysis. They used a blood flow rate of 244.5 mL/min and dialysate flow rate of 500 mL/min [8]. Wang et al. (2022) proposed a method of synchronous modulation and demodulation to improve the accuracy of spectral data. They showed that their method reduced the influence of dark current, ambient light, background noise on the signal-to-noise ratio of the spectral data and effectively avoid the error caused by the non-synchronization of the chopper and spectrometer [9]. Lint, Parker and Clermont (2023) stated that 'BUN concentration trajectory can be used to estimate clearance and adequacy of dialysis treatment. They developed two-compartment ordinary differential equations model to predict the change of BUN concentration outside and during the dialysis treatment. They concluded that their model was able to predict the BUN concentration over time and capture variance in 75 % of tested patients [10].

Nenova, Yankov and Chausheva (2024) outlined that results analysis proved a high correlation between the validated indicators of the dialysis adequacy and those with online monitoring by ionic dialysis. They stated that their established regression models confirmed the high prediction value of ionic dialysis in relation to the actually delivered dose [11].

II. THE CONTROLLED BUN DURING THE DIALYSIS PROCESS

In the work of Sano et al. (2021), they presented graphical profile of the variation of the BUN concentration over a time period of 320 minutes (min) for a number of patients during and after the dialysis process including 240 min during dialysis [12]. I have used their clinical data for patient B with a dialysis flow rate (Q_d) of 0.02 L/min as an input to identify a transfer function model for the date of the urea concentration, U_c [$G_p(s) = U_c(s) / Q_d(s)$]. The model was identified by the author using an ITAE performance index [13] and the MATLAB optimization toolbox [14]. The identified transfer function is given by a correlation coefficient of 0.9996:

$$G_p(s) = Kb_0/(s^2+a_1s+b_0) \quad (1)$$

Where:

K = process gain = -2800 (mL/dL)/(L/min)

b_0 = square of the process natural frequency = -0.07762 rad/s^2

$a_1 = 2\zeta\omega_n$ = 6.71085 rad/s

The time response profile for the input dose of 0.02 L/min with is shown in Fig.1 as generated by the step command of MATLAB [15] for the BUN change showing also the clinical data of the patient. The patient BUN limits were chosen as 8 and 24 mg/dL for adult males [1].

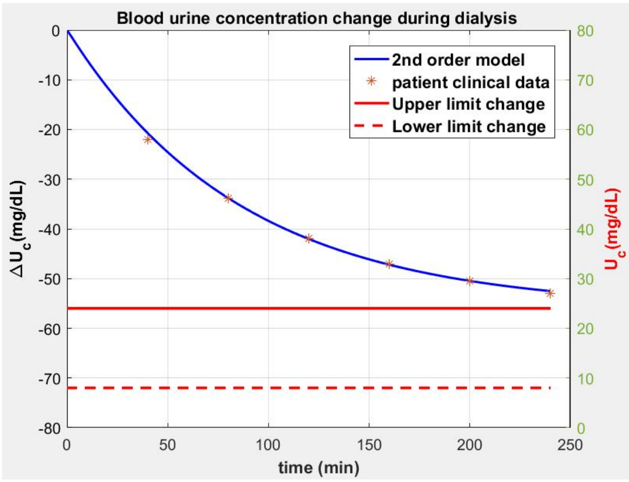


Fig.1 Step time response of the BUN as a process during dialysis.

COMMENTS:

- The BUN during dialysis is a stable process.
- Maximum overshoot: zero
- Settling time: 217.2 min

III. UBN CONTROL DURING DIALYSIS USING A PI CONTROLLER

- As a reference for control system characteristic comparison, a conventional PI controller from the first-generation of PID controllers is proposed to control the BUN.

- For purpose of controller tuning, the BUN process is written in a factorized form as shown below:

$G_p(s) = Kb_0/[(s+0.01159)(s+6.69926)]$ (2)

- The PI controller transfer function has the transfer function, $G_{PI}(s)$ given by:

$G_{PI}(s) = K_{pc1}+(K_{i1}/s)$ (3)

Where K_{pc1} and K_{i1} are the proportional and integral gains of the PI controller.

- The two elements: $G_{PI}(s)$ and $G_p(s)$ in a single-loop control system are cascaded in series.
- Multiplying $G_{PI}(s)$ by $G_p(s)$ gives the open-loop transfer function of the control system.
- Now, the closed-loop transfer function of the control system, $G_{PI}(s)G_p(s)/[1+G_{PI}(s)G_p(s)]$ can be derived using Eqs.1 and 3.
- The closed-loop transfer function of the control system will reveal a standard second-order control system with parameters function of the controller parameters K_{pc1} and K_{i1}.
- The ITAE performance index [13] as function of the error signal of the control system is used to tune the PI controller using the MATLAB optimization toolbox [14]. The result of this process gives the PI controller parameters as:

$K_{pc1} = -0.081308$, $K_{i1} = -0.100196$ (4)

- The step time response of a desired BUN change of -60 mg/dL (20 mg/dL BUN absolute value) when using a PI controller is shown in Fig.2.

COMMENTS:

- Maximum overshoot: 3.907 %
- Settling time with ± 2 % tolerance: 2.625 min
- Settling time within the BUN limits: 1.44 min
- Steady-state error: zero

Fig.2 BUN control during dialysis using a PI controller.

IV. BUN CONTROL USING AN I-FIRST ORDER COMPENSATOR

- The I-first order compensator is one of the second generation of control compensators introduced by the author since 2014. It was introduced by the author in September 2024 to control the longitudinal velocity of an autonomous car [16]. It has the transfer function, $G_{I1st}(s)$ given by [16]:

$G_{I1st}(s) = (K_{i2}/s)(s+z_2)/(s+p_2)$ (5)

Where K_{i2}, z_2 and p_2 are the integral gain, simple zero and simple pole of the I-first order compensator.

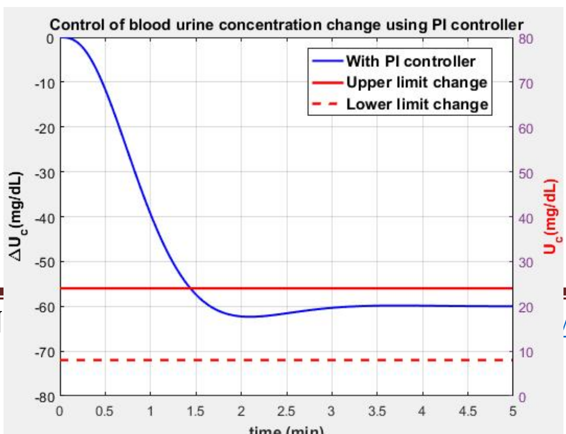
- Multiplying $G_{I1st}(s)$ by $G_p(s)$ of Eqs.5 and 2 respectively and applying the zero/pole cancellation technique [17] gives the following relationship between the compensator zero z_2 and the process pole 0.01159 as:

$z_2 = 0.01159$ (6)

- Now, the closed-loop transfer function of the control system is derived as function only of the compensator parameters p_2 and K_{i2}.
- Using an ITAE performance index [13] and the MATLAB optimization toolbox [14], the two compensator parameters are tuned and given by:

$K_{i2} = -0.61039$, $p_2 = 13.8$ (7)

- The step time response of the BUN for a -60 mg/dL desired BUN change when using an I-first order compensator is shown in Fig.3.



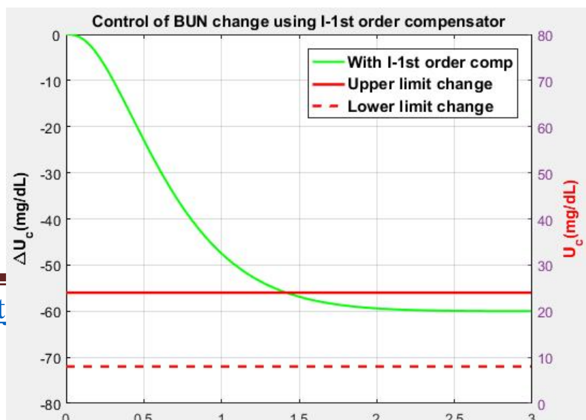


Fig.3 BUN control during dialysis using an I-first order compensator.

COMMENTS:

- Maximum overshoot: zero (compared with 3.907 % for PI controller).
- Settling time with ± 2 % tolerance: 1.80 min (compared with 2.625 min for PI controller).
- Settling time within the BUN limits: 1.42 min (compared with 1.44 min for PI controller).
- Steady-state error: zero

V. BUN CONTROL USING AN I-2/2 SECOND ORDER COMPENSATOR

- The I-2/2 second order compensator was introduced by the author in November 2024 to control the yaw angle of an autonomous car as one of the second generation of PID controllers introduced by the author since 2014. [18]. The I-2/2 second order compensator is set in the forward path of a single-loop block diagram just after the error detector. It has a transfer function, $G_{I2nd}(s)$ given by [18] :

$$G_{I2nd}(s) = (K_{i3}/s)(s+z_3)(s+z_4)/[(s+p_3)(s+p_4)] \quad (8)$$

- It has five parameters: integral gain (K_{i3}), two simple zeros (z_3, z_4) and two simple poles (p_3, p_4). The five compensator parameters have to be tuned for optimal performance of the control system.
- Using the zero/pole cancellation technique [17], in the open-loop transfer function of the control system the two simple zeros of the I-2/2 compensator in Eq.8 cancel the two simple poles of the BUN process in Eq.2 providing the values of the compensator simple zeros as:

  $z_3 = 0.01159$, $z_4 = 6.69926$ (9)
- Now, we have K_{i3}, p_3 and p_4 to tune.
- The closed-loop transfer function is derived and used to plot the step time response of the control system for the desired BUN change of -60.
- Using Routh-Hurwitz stability criterion [19], a range for the integral gain K_{i3} is related to the two simple poles p_3 and p_4 of the compensator for a stable control system as:

  .$K_{i3} < p_3p_4 (p_3+p_4)/(Kb_0)$ (10)

  Where K and b_0 are two of the process parameters in Eq.1.
- Eq.10 simplifies a manual tuning technique based on trial and error [20] by assuming values for p_3 and p_4 then use Eq.10 to set a reasonable value for K_{i3} as a percentage of K_{i3max} from Eq.10. The results of this procedure is as follows:

  $p_3 = 10$, $p_4 = 4$, $K_{i3} = -0.180366$ (11)
- The step time response of the BUN for a -60 mg/dL desired BUN change when using an I-second order compensator is shown in Fig.4.

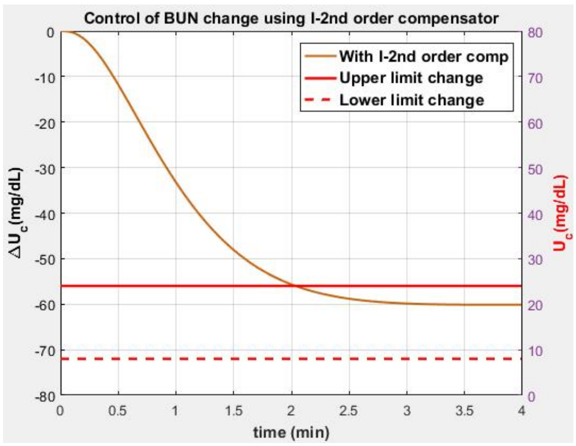


Fig.4 BUN control during dialysis using an I-second order compensator.

COMMENTS:

- Maximum overshoot: zero (compared with 3.907 % for PI controller).
- Settling time with ± 2 % tolerance: 2.50 min (compared with 2.625 min for PI controller).

- Settling time within the BUN limits: 2.02 min (compared with 1.44 min for PI controller).
- Steady-state error: zero

VI. BUN CONTROL USING A PD-PI CONTROLLER

- The PD-PI controller was introduced by the author in April 2014 to control first-order delayed processes as one of the second generation of PID controllers introduced by the author since 2014 [21]. The PD-PI controller is consisted of two cascaded control modes: PD and PI set in the single-loop block diagram of a linear control system just after the error detector. It has a transfer function $G_{PDPI}(s)$ given by:

$$G_{PDPI}(s) = (K_{pc4}+K_{d4}s)[K_{pc5}+(K_{i5}/s)] = (K_{d4}K_{pc5}/s)[s+(K_{pc4}/K_{d4})][s+(K_{i5}/K_{pc5})] \quad (12)$$

Where K_{pc4}, K_{d4}, K_{pc5} and K_{i5} are the gain parameters of the PD-PI controller.

- Multiplying $G_{PDPI}(s)$ of Eq.12 by $G_p(s)$ of Eq.2 and applying the zero/pole cancellation technique [17] gives the following relationships between the PD and PI control elements parameters as:

$$K_{pc4} = 0.01159\ K_{d4}\ ,\ K_{i5} = 6.69926K_{pc5} \quad (13)$$

- The closed-loop transfer function of the control system incorporating the PD-PI controller is derived as $M_4(s) = G_{PDPI}(s)G_p(s)/[1+ G_{PDPI}(s)G_p(s)]$. With Eq.13 it becomes:

$$M_4(s) = 1/(T_4s+1) \quad (14)$$

Where: T_4 is the time constant of the closed-loop transfer function of the control system of BUN incorporating the PD-PI controller given by:

$$T_4 = 1/(Kb_0K_{d4}K_{pc5}) \quad (15)$$

- Now, the closed-loop transfer function of the control system is that for a standard first order control system characterized by its time constant T_4. This control system has zero overshoot for any value for its time constant.
- Now we adjust its step time response performance through using its settling time. The settling time T_s of a first order control system is related to its time constant T_4 through the relationship [22].

$$T_s = 3.9\ T_4 \quad (16)$$

- For a design settling time of (say) 1.5 min, Eq.16 gives the control system time constant as:

$$T4 = 0.3846 \text{ min} \quad (17)$$

- Now, for an assumed unit value for Kpc5 in Eq.15, K_{d4} is tuned using Eqs.15 and 17 as:

$$K_{d4} = -0.011963 \quad (18)$$

- Going back to Eq.13, the two PD-PI controller parameters Kpc4 and Ki5 are tuned and given by:

$$K_{pc4} = -0.0001386\ ,\ K_{i5} = 6.69926 \quad (19)$$

- The step time response of the BUN for a -60 mg/dL desired BUN change when using a PD-PI controller is shown in Fig.5.

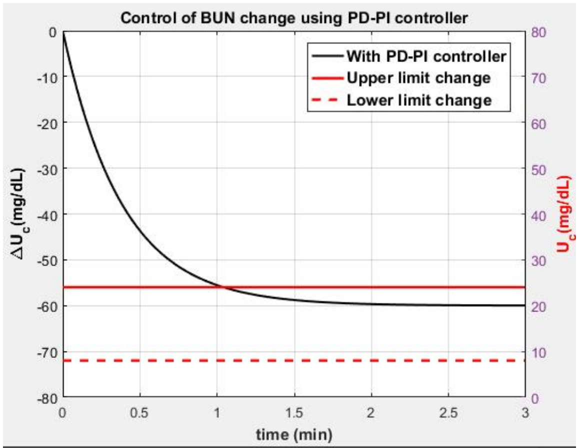


Fig.5 BUN control during dialysis using a PD-PI controller.

COMMENTS:

- Maximum overshoot: zero (compared with 3.907 % for PI controller).
- Settling time with ± 2 % tolerance: 1.50 min (compared with 2.625 min for PI controller).
- Settling time within the BUN limits: 1.0 min (compared with 1.44 min for PI controller).
- Steady-state error: zero

VII. COMPARISON OF TIME BASED CHARACTERISTICS

Graphical Comparison:

- The time-based characteristics of the control systems incorporating the proposed compensators/controllers proposed to control the BUN during dialysis are compared graphically through the step time response as depicted in Fig.6 for a desired BUN change of -60 mg/dL (20 mg/dL).

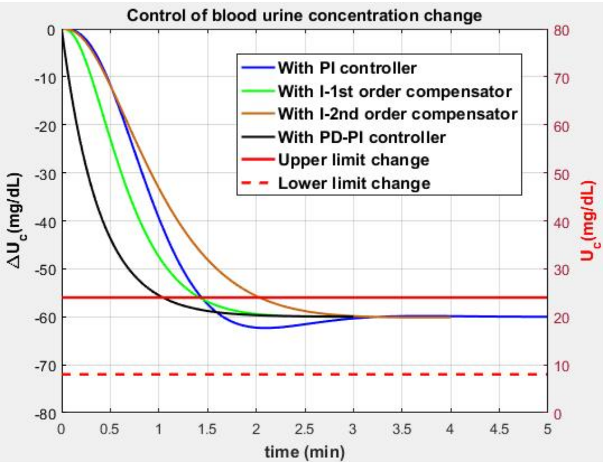


Fig.5 Graphical characteristic comparison of BUN control during dialysis.

Numerical Comparison:

- Numerical comparison for the time-based characteristics of the step time response for reference input tracking of the control system with the proposed compensators/controllers is presented in Table 1 with comparison with the application of a conventional PI controller used to control the same process.

TABLE 1
TIME-BASED CHARACTERISTICS FOR REFERENCE INPUT TRACKING OF BUN DURING DIALYSIS

Compensators/ controllers	OS_{max} (%)	$T_{s2\%}$ (%)	$T_{sLimits}$ (%)	e_{ss}
PI controller	3.907	2.625	1.44	0
I-1st order compensator	0	1.80	1.42	0
I-2nd order compensator	0	2.50	2.02	0
PD-PI controller	0	1.50	1.00	0

OS_{mas}: Maximum percentage overshoot.
$T_{s2\%}$: Settling time for ± 2% tolerance.
$T_{sLimits}$: Settling time for BUN limits.
e_{ss}: Steady-state error.

VIII. CONCLUSIONS

- The research work presented in this research paper handled the tuning of two compensators and two controllers proposed to control the BUN of a human being during dialysis.
- This was the most difficult process I faced to control since 2014. The reason for this was unavailable control techniques for direct control of the UBN outside the dialysis operation.
- On the other hand, even with the dialysis operation I didn't find ready transfer function for this process which is the stone core of any closed-loop control system.
- The paper presented one controller from the first generation of PID controllers (PI controller), two compensators from the second generation of control compensators and one controller from the second generation of PID controllers (PD-PI controller).
- The controlled process (BUN during dialysis) was identified as a second-order overdamped process when excited by a 0.02 L/min dialyzer flow rate as an input with 0.9996 correlation coefficient.
- The proposed controllers/compensator were tuned using hybrid approach based on applying the zero/pole cancellation, fulfilling some desired specific characteristics and trial and error techniques.
- All the proposed compensators/controllers succeeded to eliminate completely the steady-state error of the control system.
- The proposed I-first order, I-2/2 second order compensators and the PD-PI controller succeeded to eliminate completely the maximum percentage overshoot of the control system compared with 3.907 % for the PI controller.
- All the proposed controllers succeeded to reduce the settling time of the control system to values in the range: 1.5≤ T_s≤2.625 min compared with 217.2 min without closed-loop control.
- The PD-PI controller succeeded to reduce the settling time of the control system to 1.5

min compared with 3.907 min for the PI controller.

- The best compensator/controller is the PD-PI controller based on the minimum maximum overshoot and settling time.
- The performance of the control system based on using any of the proposed compensators/controller from the second generation is superior. However, hardware modifications of the dialysis machine have to be considered to be able to provide the levels required by the BUN control signal or make compromise between the performance parameters and control signals.

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DEDICATION

LATE PROF. ABDUL-MONEM ATTIYA

- Emeritus Associate Professor of Mechanical Engineering, Faculty of Engineering, Cairo University.
- I dedicate this research work to my dear friend Prof. Abdul-Monem Attiya.
- He is graduated from the department of mechanical engineering, Faculty of Engineering, Cairo University in 1974.
- He had his Ph. D. from the Imperial College, London in 1983.
- He taught thermodynamics and heat transfer courses for 10's of years to students of Mechanical Engineering and Mechanical Design and Production Departments.
- He supervised plenty of undergraduate and postgraduate graduation projects.
- He was an intimate friend for 10's of years because I was teaching mechanical vibrations for the Mechanical Engineering students for 27 years.
- He left us on 14 September 2023.
- I miss you Professor too much.

BIOGRAPHY

Galal Ali Hassaan

- Emeritus Professor of System Dynamics and Automatic Control.
- Has got his B.Sc. and M.Sc. from Cairo University in 1970 and 1974.
- Has got his Ph.D. in 1979 from Bradford University, UK under the supervision of Late Prof. John Parnaby.
- Now with the Faculty of Engineering, Cairo University, EGYPT.
- Research on Automatic Control, Mechanical Vibrations, Mechanism Synthesis and History of Mechanical Engineering.
- Published more than 350 research papers in international journals and conferences.
- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Chief Justice of the International Journal of Computer Techniques.
- Member of the Editorial Board of IJET.
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