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Autonomous Human Body Control, Part XIV: Serum Potassium Concentration Control during Hemodialysis using I- first Order and P-D Compensators Compared with a PID Controller

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Abstract:
This paper investigates the tuning of I-first order and P-D compensators from the second generation of control compensators and a PID controller from the first generation of PID controllers to control the serum potassium concentration of the human body during hemodialysis. The proposed compensators are tuned using a hybrid approach based on zero/pole cancellation and the satisfaction of specific time-based characteristics of the closed-loop control system incorporating the compensator and process. The serum potassium concentration is modeled using pre-published hemodialysis profile-data and the tuning results of the proposed compensators/controller are presented and applied to generate the step time response for reference input tracking of a specific level within the normal limits of the serum potassium concentration. The characteristics of the step time responses are compared with those of the conventional PID controller. The best compensator/controller for the control of the human serum potassium concentration during hemodialysis is assigned. Clearance rate of serum potassium

Keywords **— Autonomous human body control, serum potassium concentration control during hemodialysis, PID controller, I-first order compensator, P-D compensator, controller/compensators tuning.**

I. INTRODUCTION

This is the fourteenth 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 serum potassium concentration during the dialysis operation to maintain a potassium concentration level with the normal range of 3.5 to 5.0 mmol/L (13.6843 to 19.5490 mg/dL) [1]. Increased serum potassium concentration levels than 5.0 mmol/L (19.5490 mg/dL) results in '*hyperkalemia*' resulting in a number of symptoms on the human health including: Abdominal pain, diarrhea, nausea, vomiting in case of mild hyperkalemia [2]. For severe hyperkalemia symptoms may be: Chest pain, heart palpitations, irregular heartbeats, muscle weakness and numbness in limbs [2]. Here are some of the research efforts in presenting some aspects related to serum potassium concentration levels during hemodialysis since 2000:

Cohn et al. (2000) presented the result of the National Council on potassium in clinical practice. They outlined that the primary outline of the meeting was the development of guidelines for potassium replacement therapy intending to provide a general approach to the prevention and treatment of hypokalemia [3]. Santaro et al. (2005) outlined that there is a need to achieve an adequate remove of potassium with the risk of cardiac arrhythmias due to sudden intra-extracellular potassium gradient. They concluded that it is not the potassium dialysis removal alone that can be destabilizing from an electrophysiological standpoint, but its removal dynamics. They presented potassium concentration profile acetate-free biofiltration for time span up to 240 minutes [4]. Sanchez et al. (2007) considered an study on 36 patients receiving hypodialysis for more than two months. Their results for serum potassium concentration was 5.07 mmol/L for pre-hemodialysis (mean value) and 3.21for post-hemodialysis. They concluded that the electrocardiogram continued to be a useful tool for early detection of hyperkalemia [5]. Gabutti et al. (2011) outlined that rapid decrease of serum potassium concentrations during hemodialysis produces significant increase in blood pressure at the end of the session. They concluded that the risk of intra-dialysis hypotension inversely correlated to the potassium concentration in the dialysate [6].

Agar et al. (2017) outlined that low dialysate potassium concentration to decrease serum potassium levels is associated with a high incidence of sudden cardiac arrest or sudden death. They concluded that rapid and substantial intradialysis decreases in serum potassium concentration has to

be avoided while maintaining adequate potassium removal [7]. Karaboyas et al. (2017) outlined that there is increase association between dialysate potassium concentration and predialysis serum potassium level. They concluded that high predialysis serum potassium level was associated with increased risk for adverse events and it was observed minimal association between dialysate potassium concentration and serum potassium measured before dialysis [8]. Depret et al. (2019) outlined that hyperkalemia is a potentially life-threatening electrolyte abnormality and may cause cardio electrophysiological disturbances in the acutely ill patients. They presented a serum kinetic potassium concentration for four hours hemodialysis in mmol/L, other profiles for 12 hours hemodialysis and another profile for 24 hours hemofiltration [9]. Shibata and Uchida (2022) outlined that the elevation in serum potassium levels is one of the most common complications in patients with maintenance hemodialysis. They reviewed the literature on potassium physiology in maintenance hemodialysis patients and summarized the findings on dialysate prescription and pharmacological therapy [10].

Hamada et al (2024) outlined that studies reported that excess decrease of potassium concentration in plasma during treatment is associated with destabilization of cardiac function. They investigated the relationship between plasma potassium concentration dynamics and cardiomyocyte excitability for the first time using an electrophysiological mathematical model. They concluded that it it is necessary to implement personal prescription or optimal control of potassium concentration in dialysis fluid based on predialysis plasma potassium concentration [11]. Charytan et al. (2025) outlined that the optimal approach towards managing serum potassium and dialysate potassium concentration was uncertain. They investigated potassium concentration of 3.0 mmol/L with sodium zirconium cyclosilicate (SZC) compared with using 2.0 mmol/L dialysate potassium concentration alone. They concluded that in patients with hyperkalemia on maintenance hemodialysis, a comparison of dialysate potassium 3.0 mmol/L and SZC on non-hemodialysis days reduced the rate of atrial fibrillation, significant arrhythmias and post-dialysis hypokalemia compared with 2.0 mmol/L dialysate potassium concentration [12].

II. THE CONTROLLED POTASSIUM CONCENTRATION DURING DIALYSIS AS A PROCESS

In their investigation of hyperkalemia in acutely ill patients, Depret et al. presented kinetic potassium concentration profiles for 4, 8 and 12 hours hemodialysis in mmol/L units [9I considered the 12 hours profile, digitized it for 2 hours interval and transformed it to mg/dL units. Also, I transferred the resulting digital profile to changes taking the first value as a reference value (zero value) for sake of dynamic model identification for the potassium concentration process transfer function. In this case, the steady state value of the potassium concentration time response (ΔK_{ss} is -12.7576 mg/dL at 10 hours' time. The input dialysate potassium dose is assumed to be 3 mmol/L (D_p = 11.7294 mg/dL) recommended to start with [13]. In such a case the steady state gain of the potassium concentration, K_p will be:

$$K_p = \Delta K_{ss} / D_K = -1.08766 \quad (1)$$

The shape of the potassium kinetic profile indicates that this process is a first-order one. Using an ITAE performance index [14] minimized using the MATLAB optimization toolbox [15], the serum potassium concentration transfer function $G_K(s)$ with correlation coefficient of 0.9975 is given by:

$$G_K(s) = K_p / (T_p s + 1) \quad (2)$$

Where the process time constant T_p in hours is identified as:

$$T_p = 3.1895 \quad (3)$$

The time response profile for an input dose change of 11.7294 mg/dL dialysate potassium is shown in Fig.1 as generated by the '*step*' command of MATLAB [16] for the serum potassium change.

COMMENTS:

- The serum calcium concentration following dialysate potassium input is a stable process.
- Maximum overshoot: zero
- Settling time with ± 2 % tolerance: 12.477 h
- Rise time: 7.007 h

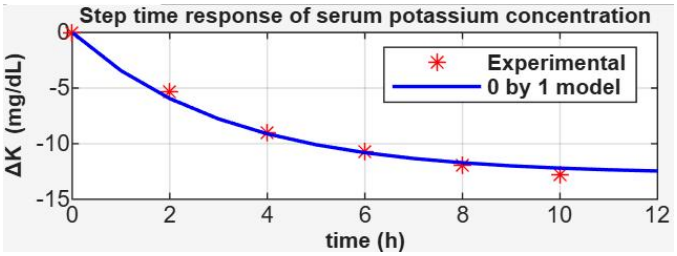

Fig.1 Step time response of the potassium concentration.

III. SERUM POTASSIUM CONTROL DURING DIALYSIS USING A PID CONTROLLER

- As a reference for control system characteristic comparison, a conventional PID controller from the first-generation of PID controllers is proposed to control the serum potassium concentration.
- I was asked when publishing one of my papers from one of the paper referees: why PID?. The answer is discussed in details by Haggland and Gupman [17].
- A PID controller has the transfer function, $G_{PID}(s)$ given by:

$$G_{PID}(s) = K_{pc1} + (K_{i1}/s) + K_{d1}s = (K_{d1}s^2 + K_{pc1}s + K_{i1})/s \quad (4)$$

Where K_{pc1}, K_{i1} and K_{d1} are the proportional, integral and derivative gains of the PID controller.

- The two elements: $G_{PID}(s)$ and $G_K(s)$ in a single-loop control system are cascaded in series.
- The controller parameters K_{pc1}, K_{i1} and K_{d1} are tuned through the minimization of an ITAE performance index [14] using the MATLAB optimization toolbox [15]. The result of this process gives the tuned PID controller parameters as:

$$K_{pc1} = -3.3479,\ K_{i1} = -1.3246,\ K_{d1} = 0.2410 \quad (5)$$

- The step time response of a desired potassium concentration of 16 mg/dL (-8.487 mg/dL change) when using a PID controller to control the serum potassium concentration process is shown in Fig.2. Lower and upper limits of -10.8027 and -4.9380 mg/dL respectively [1] are shown also in Fig.2.

COMMENTS:

- Maximum overshoot: zero
- Settling time with ± 2 % tolerance: 2.3737 h
- Settling time within the calcium concentration limits: 0.7187 h
- Settling time within the potassium concentration limits: 0.7419 h
- Delay time: 0.608 h
- Rise time: 1.519 h
- Steady-state error: zero

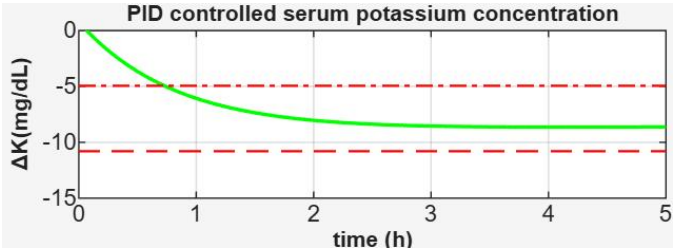

Fig.2 Serum potassium concentration control using a PID controller.

IV. SERUM POTASSIUM CONCENTRATION CONTROL USING AN I-FIRST ORDER COMPENSATOR

- The I-first order compensator was introduced by the author in September 2024 to control car longitudinal velocity as one of the second generation of control compensators introduced by the author since 2014 [18]. The I-first order compensator is composed of two cascaded control elements: I-control mode and a conventional first-order compensator set in the single-loop block diagram of a linear control system just after the error detector. It has a transfer function $G_{I1st}(s)$ given by:

$$G_{I1st}(s) = (K_{i2}/s)(T_{z2}s+1)/(T_{p2}s+1) \quad (6)$$

Where K_{i2}, T_{z2} and T_{p3} are the compensator integral gain, simple zero time constant and simple pole time constant respectively

- The three gain parameters of the compensator are tuned as follows:

In the open-loop transfer function of the closed-loop control system comprising the

compensator and the process, the zero/pole cancellation technique [19] is used to cancel the compensator zero with the process pole giving:

$$T_{z2} = 3.1895 \text{ h} \quad (7)$$

- The closed-loop transfer function of the control system now becomes:

$$M_2(s) = \omega_{n2}^2 / (s^2 + 2\varsigma_2\omega_{n2}s + \omega_{n2}^2) \quad (8)$$

- Where ω_{n2} is the control system natural frequency given by:

$$\omega_{n2}^2 = K_p K_{i2} / T_{p2} \ , \ 2\varsigma_2\omega_{n2} = 1/T_{p2} \quad (9)$$

- The closed-loop transfer function of the control system incorporating the I-first order compensator given by Eq.8 is defining a standard 0/2 second-order dynamic system. Such a dynamic system has zero maximum overshoot if its damping ratio is unity (critically damped system).
- The settling time to 2 % tolerance band for the 0/2 second-order control system is related to its natural frequency through the relationship [20]:

$$T_{s2} = 5.8355 / \omega_{n2} \quad (10)$$

- Assume that it is desired to have a 0.5 h settling time for the I-first order controlled potassium concentration process, then Eq.10 gives ω_{n2} as:

$$\omega_{n2} = 11.671 \text{ rad/h} \quad (11)$$

- The settling time to 2 % tolerance for the 0/2 second-order dynamic system is related to its natural frequency through the relationship [20]:

$$T_{s2} = 5.8355 / \omega_{n2} \quad (12)$$

- For a desired settling time of (say) 0.5 h, Eq.12 gives the natural frequency of the potassium concentration dynamic system as:

$$\omega_{n2} = 11.671 \text{ rad/h} \quad (13)$$

- Now, Eq.9 gives the other two parameters of the compensator (T_{p2} and K_{i2}) as:

$$T_{p2} = 0.0428 \text{ h and } K_{i2} = -5.3652 \quad (14)$$

- The step time response of a desired potassium concentration of 16 mg/dL (-8.487 mg/dL change) when using an I-first order compensator to control the serum potassium concentration process is generated using Eqs.9,7,14 using the 'step' command of MATALB [16] and shown in Fig.3.

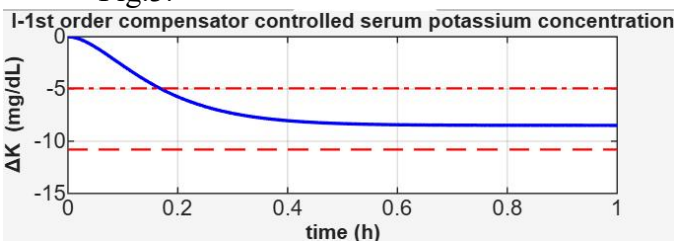

Fig.3 Serum potassium concentration control using an I-first order compensator.

COMMENTS:

- Maximum overshoot: zero.
- Settling time with ± 2 % tolerance: 0.50 h (compared with 2.3737 h for the PID controller).
- Settling time within the potassium concentration limits: 0.1667 h (compared with 0.7187 h for the PID controller).
- Delay time: 0.1438 h (compared with 0.6080 h for the PID controller).
- Rise time: 0.2877 h (compared with 1.5190 h for the PID controller).
- Steady-state error: zero

V. SERUM POTASSIUM CONCENTRATION CONTROL USING A P-D COMPENSATOR

- The P-D compensator was introduced by the author in January 2022 to control a highly oscillating second-order-like process as one of the second generation of control compensators introduced by the author since 2014 [21]. Fig.4 shows the structure of the P-D compensator [21] with control modes having transfer functions $G_{c1}(s)$ in the forward path and $G_{c2}(s)$ in the feedback path. $G_{c1}(s)$ and $G_{c2}(s)$ are defined as:

$$G_{c1}(s) = K_{pc3} \ , \ G_{c2}(s) = K_{d3}s \quad (15)$$

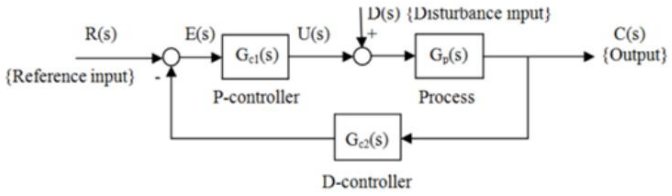

Fig.4 Structure of a P-D compensator [21].

Where K_{pc3} and K_{d3} are the gain coefficients of the P-D compensator to be tuned for good control system performance as follows:

- Using the block diagram in Fig.4, the closed loop transfer function $M_3(s)$ of the control system is:

$$M_3(s) = K_p K_{pc3} / (T_3 s + 1)$$
$$where T_3 = T_p + K_p K_{pc3} K_{d3} \quad (16)$$

- The control system according to Eq.16 is a standard first-order one having a time constant T_3.
- For a zero steady-state error, $K_p K_{pc3}$ must equal 1 in Eq.16 giving:

$$K_{pc3} = -0.9194 \quad (17)$$

- The settling time of first-order systems with 2 % tolerance is related to its time constant through the relationship [22]:

$$T_{s3}(s) = 4T_3 \quad (18)$$

- Let the desired settling time is 0.5 h. Then Eqs.16 and 17 gives the derivative gain as:

$$K_{d3} = -2.4895 \quad (19)$$

- The transfer function in Eq.16 and the tuned controller gain in Eqs.17 and 19 produce the step time response of the serum potassium concentration shown in Fig.5.

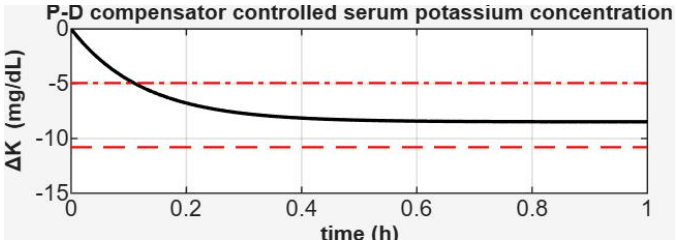

Fig.5 Serum potassium concentration control using a P-D compensator.

COMMENTS:

- Maximum overshoot: zero.
- Settling time with ± 2 % tolerance:0.4890 h (compared with 2.3737 h for the PID controller).
- Settling time within the calcium concentration limits: 0.1063 (compared with 0.7187 h for the PID controller).
- Delay time: 0.0867 h (compared with 0.6080 h for the PID controller).
- Rise time: 0.2746 h (compared with 1.5190 h for the PID controller).
- Steady-state error: zero

VI. COMPARISON OF TIME BASED CHARACTERISTICS

Graphical Comparison:

- The time-based characteristics of the control systems incorporating the controller/compensators proposed to control the serum potassium concentration during dialysis are compared graphically through the step time response as depicted in Fig.6 for a desired potassium concentration change of 16 mg/dL (-8.487 mg/dL change).

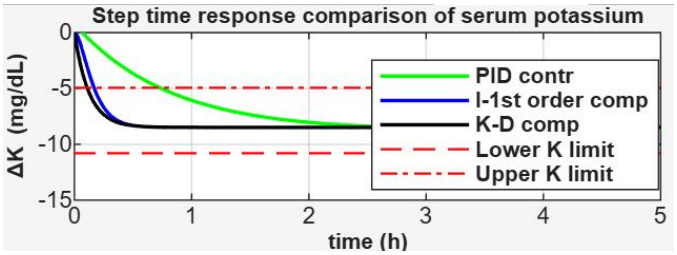

Fig.6 Graphical characteristic comparison of serum potassium control during dialysis.

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 is presented in Table 1 with comparison with the application of a conventional PID

TABLE 1
TIME-BASED CHARACTERISTICS FOR CONTROLLER/COMPENSATORS COMPARISON

Controller/ compensators	PID controller	I-first order compensator	P-D compensator
OS_{max} (%)	0	0	0
$T_{s2\%}$ (h)	2.3737	0.500	0.4890
$T_{sLimits}$ (h)	0.7419	0.1667	0.1063
T_d (h)	0.6080	0.1438	0.0867
T_r (h)	1.5190	0.2877	0.2746
e_{ss} (mg/dL)	0	0	0

OS_{max}: Maximum percentage overshoot.
$T_{s2\%}$: Settling time to 2% tolerance.
$T_{sLimits}$: Settling time to Normal limits of serum potassium concentration.
T_d: Delay time.
T_r: Rise time.
e_{ss}: Steady-state error.

controller used to control the same potassium concentration process.

VII. POTASSIUM CLEARING RATE DURING HEMODIALYSIS

While preparing the literature survey of this research work, I found some dangerous statements about the serum potassium clearance rate during hemodialysis. Some researchers said that there is a risk of cardiac arrhythmias due to sudden potassium gradient [4]. Other mentioned sudden cardiac arrest or sudden death [7] and destabilization of cardiac functions [11]. On the other hand, I did not find any indication of available limit for serum potassium clearance rate in the literature. Therefore, I decided to present the effect of settling time of the step time response of potassium clearance when using the P-D compensator to control the serum potassium concentration level during hemodialysis.

Step Time Response:

A set of time response settling time of: 2, 4, 6 and 8 h, Eq.18 gives the time constant T_3 of the closed-loop control system as: 0.5, 1, 1.5 and 2 h. Eq.16 is used to generate the step time response for a desired potassium concentration change of -8.487 mg/dL using MATLAB command 'plot' [16] as shown in Fig.7.

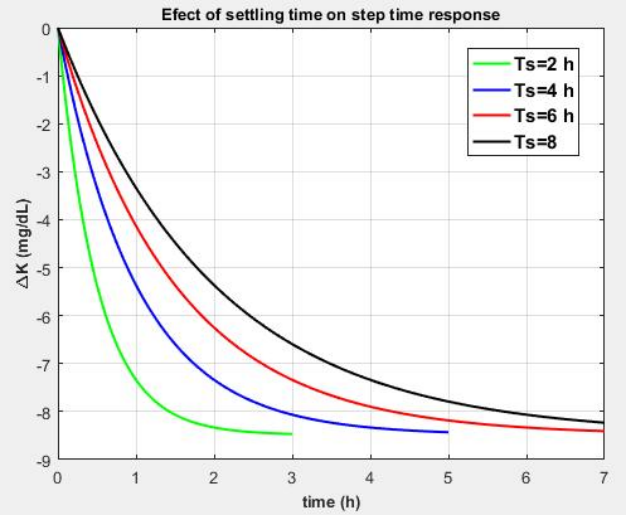

Fig.7 Step time response with P-D compensator-controlled serum potassium concentration during dialysis.

Potassium Concentration Clearance Rate

The potassium clearance rate (CR) is defined mathematically as dK/dt where K is the potassium concentration as function of time. It can be obtained either from the step time response of the potassium concentration or from the transfer function of the clearance rate $CR(s)/A_d(s)$ obtained from Eq.16. Using any of them generates the potassium clearance rate time response shown in Fig.8.

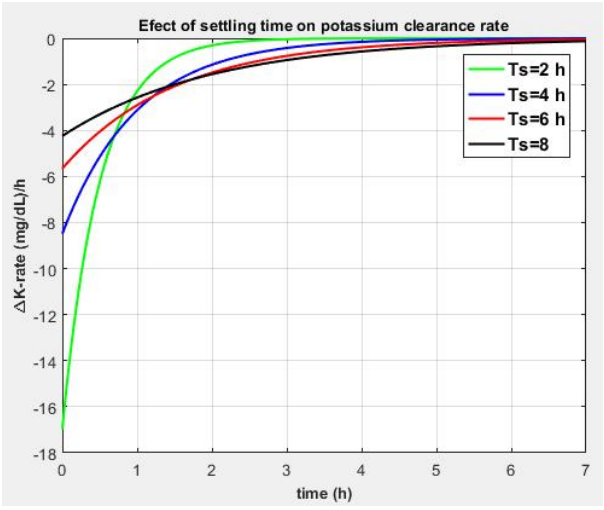

Fig.8 Potassium clearance rate response with P-D compensator-controlled serum potassium concentration during hemodialysis.

VIII. CONCLUSIONS

- The research work presented in this research paper handled the tuning of two compensators from the second generation of control compensators proposed to control the serum potassium concentration of a human being during dialysis compared with a PID controller from the first generation of PID controllers.
- The controlled serum potassium concentration as a process was identified as a first-order one. Its parameters were identified using kinetic profile data from a previous research work.
- The proposed compensators were tuned using hybrid approach based on applying the zero/pole cancellation and specific step time response characteristics (critical damping, settling time and steady-state error).
- The PID controller was tuned using an ITAE performance index and MATLAB optimization toolbox.
- The proposed compensators/controller succeeded to eliminate completely the steady-state error of the control system.

- The proposed compensators/controller succeeded to eliminate completely the maximum percentage overshoot of the control system.
- The proposed compensators succeeded to reduce the settling time of the control system (with respect to the 2 % tolerance) to values in the range: $0.489 \leq T_{s2\%} \leq 0.50$ h compared with 2.3737 h for the PID controller.
- The proposed compensators succeeded to reduce the settling time of the control system with respect to normal potassium concentration limits to $0.1063 \leq T_{sLimits} \leq 0.1667$ h compared with 0.7419 h for the PID controller.
- The proposed compensators succeeded to reduce the delay time to $0.0867 \leq T_d \leq 0.1438$ h compared with 0.6080 h for the PID controller.
- The proposed compensators succeeded to reduce the rise time to $0.2746 \leq T_r \leq 0.2877$ h compared with 1.5190 h for the PID controller.
- The best compensator is the P-D compensator based on the characteristics in Table 1.
- The effect of control system settling time to 2% tolerance ($T_{s2\%}$) on the step response of the control system when the P-D compensator is proposed to control the serum potassium concentration was investigate for $T_{s2\%}$ in the range: $2 \leq T_{s2\%} \leq 8$ h.
- The effect of control system settling time to 2% tolerance ($T_{s2\%}$) on the rate of potassium clearance during hemodialysis when the P-D compensator is proposed to control the serum potassium concentration was investigate for $T_{s2\%}$ in the range: $2 \leq T_{s2\%} \leq 8$ h.
- The maximum clearance rate was in the beginning of the step input activation depending on the settling time of the control system step time response.
- Future work is required to set limits for the clearance rate of serum potassium concentration to avoid cardiac effects and possibility of patient death during hemodialysis.

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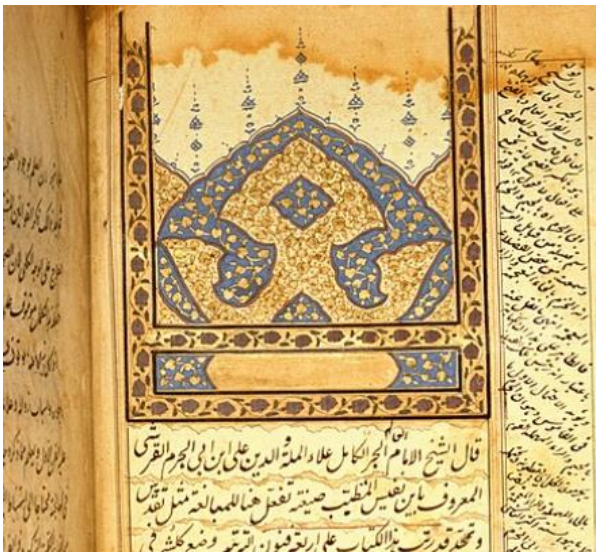
DEDICATION



IBN AL_NAFIS [23]

- Arab physician, anatomist and philosopher.
- Born near Damascus of Syria in 1210 AC.
- Started studying medical studies at the Nuri Hospital in Damascus ate age of 16.
- Transferred to Egypt when he was 25 and became the Chief Physician in the Al-Mansouri Hospital in Cairo.
- Was the first to describe the pulmonary circulation of blood.
- Provided insights into the coronary circulation (blood supply to the heart muscle).
- Wrote over 110 medical books.
- He was considered as the '*father of circularity physiology*'.
- This is why I dedicated this research work to him.

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 360 research papers in international journals and conferences.
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