System Dynamics Highlights the Effect of Maintenance on Hemodialysis Performance

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Abstract- The Kt/V value demonstrates the dose of hemodialysis (HD). Several studies suggest an association between hemodialysis machine maintenance and patient outcomes. It has been suggested that there is a correlation between dose of dialysis and machine maintenance. However, in spite of the current practice, there are conflicting reports regarding the relationship between dose of dialysis or patient outcome, and machine maintenance. In this article, we will discuss the impact of hemodialysis machine maintenance on dialysis adequacy Kt/V and session performance by building a system dynamics model to evaluate the effect of machine maintenance on session performance. We will also mention the interrelationships of dialysis dose and machine maintenance with respect to these patients.

Key words: Urea kinetic modelling, Hemodialysis, Dialysis adequacy, System dynamics, Hemodialysis machine maintenance.

I. INTRODUCTION

The most widely used definition of the dose of dialysis is fractional clearance of body water for urea—the product of dialyzer urea clearance (K) and treatment time (t) divided by the urea distribution volume (V), or Kt/V [1-5]. Not all hemodialysis patients receive their prescribed dose of hemodialysis [6,7]. Some studies suggested that only 50% of end stage renal disease (ESRD) patients in the United States actually receive their prescribed hemodialysis dose. To prevent the Kt/V for any patient from declining to values below the recommended minimum delivered dose, practitioners should prescribe doses of hemodialysis that are greater than these minimum values, nephrologists should prescribe doses of hemodialysis that are higher than the aforementioned minimum delivered levels [8]. Therefore, the HD Adequacy Work Group suggests that the prescribed minimum Kt/V be 1.3 for patients dialyzing three times per week. A variety of factors may result in the actual delivered dose of hemodialysis falling below the prescribed dose [6,9,10,11].

Common factors include reduction in treatment time, ineffective urea clearance due to access recirculation, inadequate blood flow to the dialyzer, dialyzer clotting, low blood pump and dialysate flow, or underestimates of flow due to calibration errors and blood pump tubing collapse that related to hemodialysis machine maintenance. Maintenance must be inclusive of periodic maintenance, troubleshooting, and problem maintenance. Perfect preventive maintenance means that the system is restored to good as new condition. Imperfect preventive maintenance restores the system to a condition that is between "good as new" and "bad as old". All maintenance must be performed so that equipment and systems operate efficiently and effectively. Improper maintenance and repairs can lead to unsafe conditions and reduced system performance. A strong preventive maintenance program can help in reducing the frequency of emergency and much corrective maintenance and helps utility managers be aware of, and plan for, capital equipment replacement. With this in mind, the well-run maintenance system should provide significant benefits in terms of performance, longevity, and operating cost control. Hemodialysis machine maintenance is extremely important in evaluation of adequacy of hemodialysis and in assessing dialysis session performance. The calibration of dialysate pump and blood pump during periodic maintenance is an essential component to delivering the prescribed hemodialysis treatment. It is important to know the dialysis machines (i.e., how they work?, are machines truly volumetric?, what is the facility's procedure to replace/repair hemodialysis machines?, who does machine maintenance?, how often is dialysis staff in serviced on machine issues?, and/or what is the facility's procedure for periodic maintenance?). The dialysate and blood pump must be kept in calibration in order to deliver the settings on the machine. The clock must be accurate for the dialysate and ultrafiltration time. Routine preventative and annual maintenance is vital to provide a safe and adequate dialysis and must be conducted with careful attention and in a timely fashion. Proper setting of the dialysis machine to achieve the prescribed blood flow rate can also significantly impact adequacy over time. Table 1 indicates even a 5-ml decrease in the prescribed blood flow rate will make a significant impact over a week, a month, and a year's time. Machine maintenance is extremely important as the machine may indicate the correct blood flow rate (BFR); but, if not calibrated correctly it may be delivering more or less. Frequent observation for fluctuating or decreased blood flow rate can also positively impact the delivery of the prescribed BFR. Frequent interruption of the blood flow rate may cause a loss of blood volume as well. Needles and bloodlines should be assessed for positioning and corrected as soon as possible. Needle and bloodline size should be considered if difficulty in achieving blood flow and Kt/V is a persistent problem. Also, care must be given to ensure that the machine is set for the prescribed dialysate flow rate. Again, machine maintenance is vital in the delivery of the prescription. If the dialysate pump is not correctly calibrated the machine will not deliver the prescribed dialysate flow rate.

Table 1 Blood Volume Not Cleaned due to a 5 ml Decrease in Prescribed Blood Flow Rate [12]

BFR 5ml/min (300 ml/hour) less than Prescribed	**3 Hour Dialysis : Loss of Blood Not Dialyzed as Prescribed**	**4 Hour Dialysis : Loss of Blood Not Dialyzed as Prescribed**	**5 Hour Dialysis: Loss of Blood Not Dialyzed as Prescribed**
Per Treatment	900 ml	1,200 ml	1,500 ml
Per Week	2,700 ml	3,600 ml	4,500ml
Per Month	10,800 ml	14,400 ml	13,500 ml
Per Year (52 Weeks)	140,400 ml	187,200 ml	234,000 ml

II. METHODOLOGY

A. Research Design

The model discussed in [13] was developed using Vensim DSS v 4.0a simulation software for formulating, analyzing and comparing various policies to determine optimum level of dialysis parameters for improved session performance. The simulation results with base case values and with different test scenarios are presented in [13]. The base case values were selected based on the experts experience in the field of nephrology and the insights from the research literature. The research analysis started by developing the mental model (Dialysis performance causal loop diagram explaining and understanding the complex cause and effect relationships existing between maintenance and dialysis performance.

B. Model Description

Figure 1 shows the overall causal loop diagram of the system. The causal loop diagram shown below is divided into two models: (1) The intradialytic model (during dialysis session) which analyzing the dynamic behavior of various factors that characterizes and controlling the hemodialysis session management process and (2) The interdialytic model (between dialysis sessions) which identifying the effect of increasing dialysis adequacy on nutritional status of the patient which in turn reduces the morbidity rate and the intradialytic complications that lead to session degradation. First we will analyze the behavior of the system for 240 minute time period. This time period for simulation was decided based on the period of dialysis treatment sessions and it is the time for intradialytic model. After that the time horizon was expanded for 10080 minutes to estimate the weekly BUN profile of the patient and it is the time for interdialytic model. Therefore, the simulation control parameters that were used for conducting various simulation runs with different scenarios including the base case values are listed below:

FINAL TIME (The final time for the simulation) = 10080 Minute
INITIAL TIME (The initial time for the simulation) = 0 Minute
TIME STEP (The time step for the simulation) = 1 Minute

A time step of 1 minute was used so as to give smooth time profiles for the different variables in the model. This time step is used to calculate some parameters in the simulation model. The change in model time step will affect the accuracy of the results and hence the model has not been tested for shorter or longer time steps.

Because the causal loop diagrams are excellent for quickly capturing the hypothesis about the cause of dynamics, eliciting and capturing the mental models and communicating important feedbacks [14], the following hypotheses are proposed

1. The overall dialysis session performance is not only a function of dialysis adequacy but also depends on the frequency of intradialytic complications and overall equipment effectiveness.

2. Session degradation reduction improves session performance by reducing intradialytic complications episodes and increasing equipment effectiveness over time.

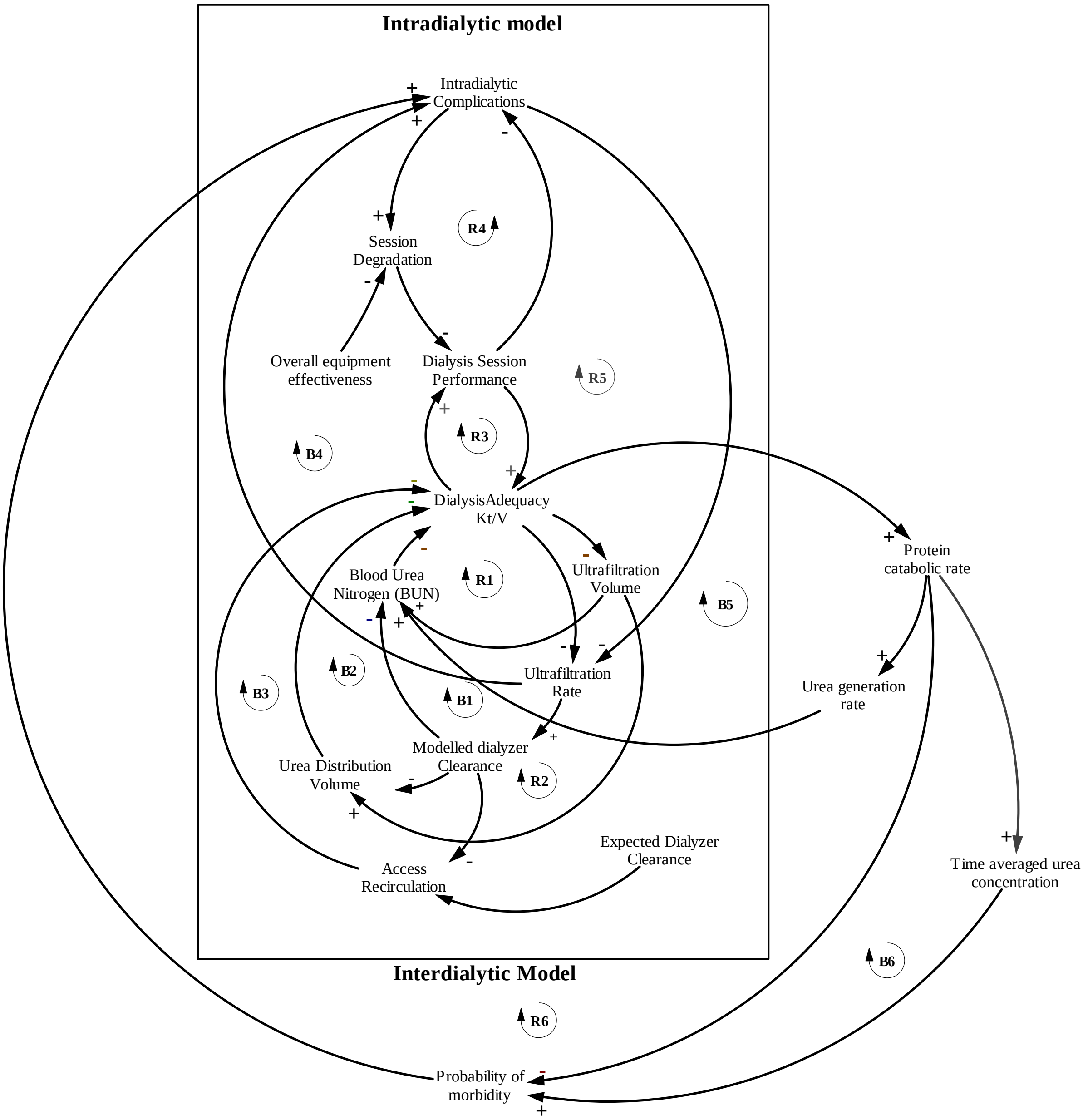

Fig.1. The Overall Causal Loop Diagram Of Hemodiadynamics [13]

Figure 2 shows the loops that highlight the effect of dialysis adequacy and session degradation on session performance. The hemodialysis session degradation depends on the overall equipment effectiveness and the intradialytic complications. The first positive feedback loop (R1) showing that as dialysis adequacy increases, it increases the session performance which in turn increases the delivered dialysis dose. This loop can be used to test the first hypothesis stated earlier. The second positive feedback loop (R2) showing that the increase in the intradialytic complications will increase the session degradation which in turn decreases the session performance. Decrease in session performance increases the probability of complications during dialysis. This loop can be used to test the second hypothesis.

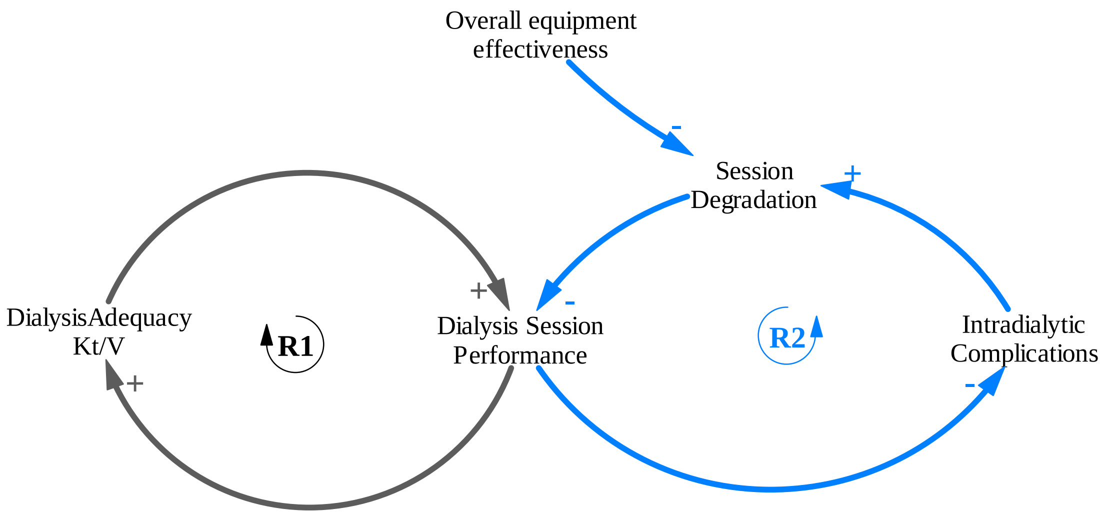

Figure 2. Feedback Structure showing the effect of dialysis adequacy and session degradation on the overall hemodialysis performance

C. Formulating a Simulation Model (Stock & Flow Diagram)

This next step in modeling involves setting up a formal model complete with equations, parameters and initial conditions that represent the system. The overall stock and flow diagram was shown in [13] and is shown also in appendix. For each subsystem the assumed parameters, initial values, variable were ranged to be entered to the system for the sake of building the stock & flow diagram. After that the equations and graphs that describe the relationships between the various variables were entered to the system using the Vensim DSS software and were elicited from the experts in the field of nephrology. They were asked for their inputs on the units for measurement of different variables, the functional form of the various equations between variables, parameters of these equations (elicited through graphical portrayal of key relationships), and the initial values of all stock variables. To show the effect of the maintenance on the overall hemodialysis session performance, two structures will be described from the overall stock & flow diagram. These two structures are the hemodialysis session degradation and the overall session performance.

a. Hemodialysis Session Degradation Structure

Dialysis session degradation structure is shown in figure 3. Session degradation is caused because of two factors; complications and equipment deficiency.

Session Degradation = IF THEN ELSE (Session Degradation due to Complications + Effect of Equipment deficiency on Session Degradation (Session Degradation due to Equipment deficiency) >1, 1, Session Degradation due to Complications + Session Degradation due to Equipment deficiency) (1)

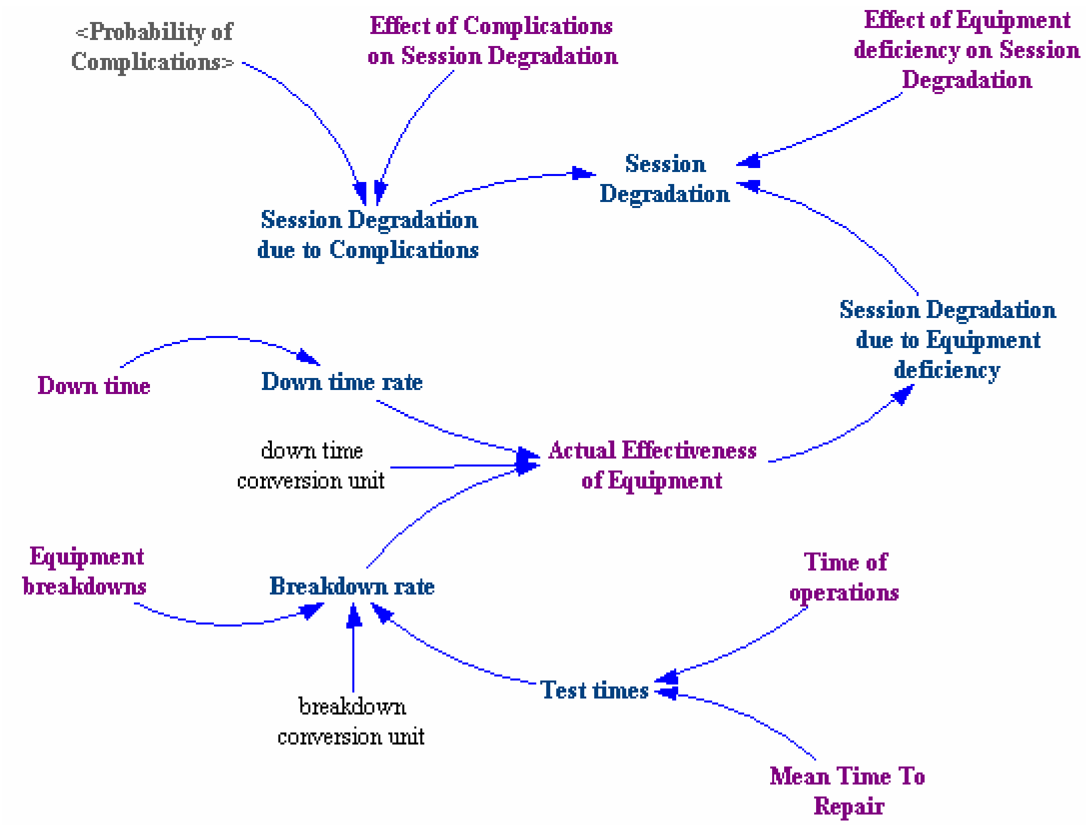

Figure 3 The Dialysis Session Degradation Structure

Session degradation is the addition of session degradation due to complications and session degradation due to equipment deficiency. Session degradation varies from 0 to 1. It can not take value greater than 1. If the additive impact of complications and equipment deficiency in session degradation is more than 1, its value is limited to 1 which indicated that the session is totally degraded. Figure 4 shows the effect of complications on the session degradation.

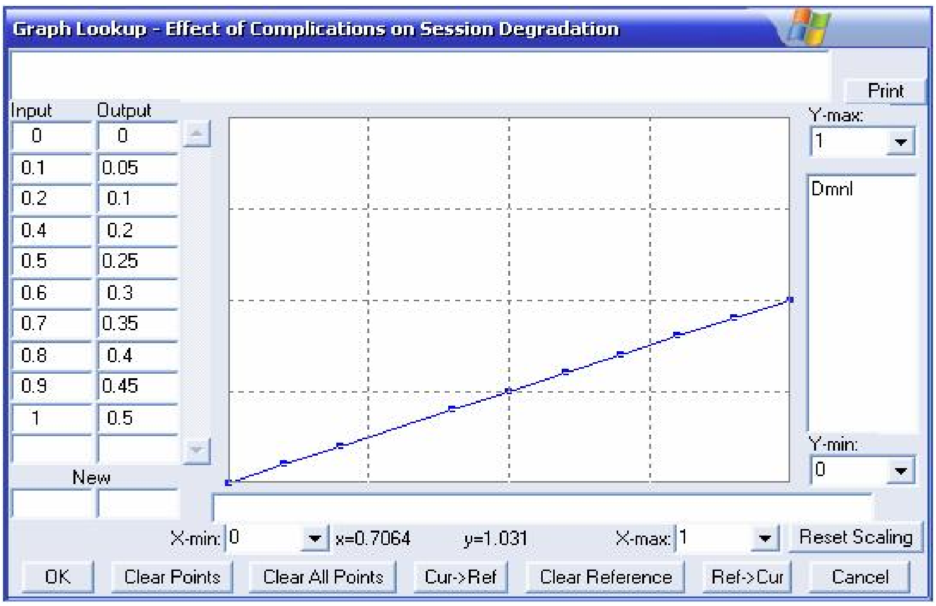

Figure 4 The Effect Of Complications On The Session Degradation.

There is a non-linear relationship between session degradation and the equipment deficiency. The rate of session degradation increases with the increase in equipment deficiency. The lookup table (figure 5) shows the non-linear relationship in graphical format.

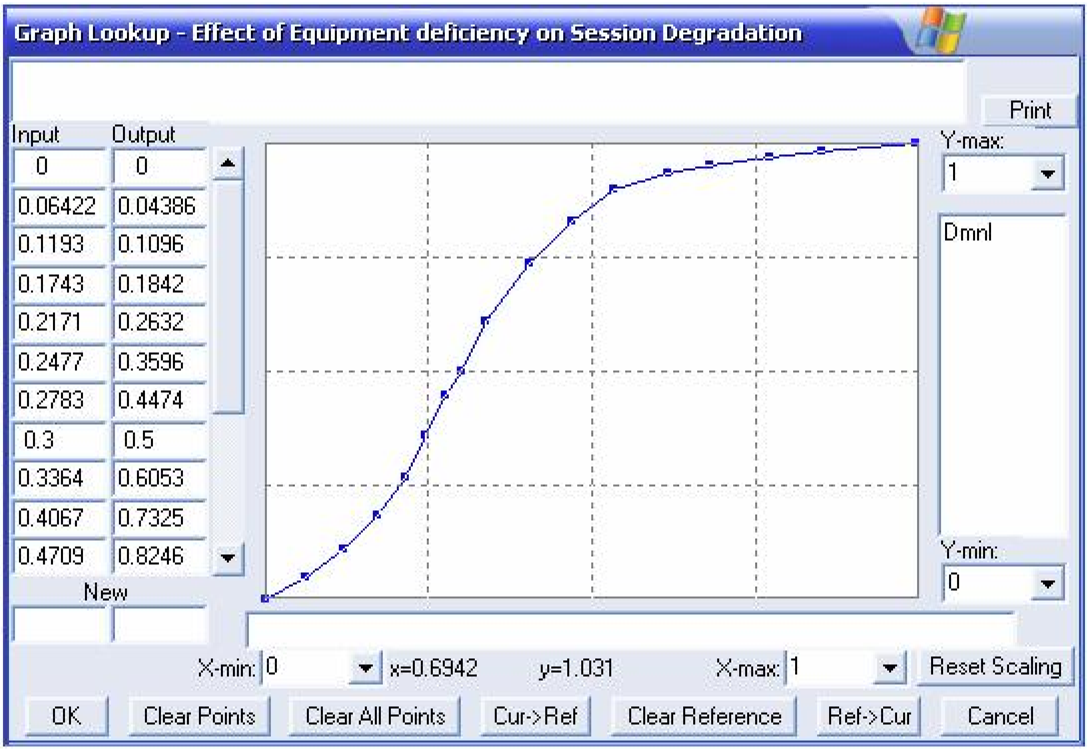

Figure 5 The Effect Of Equipment Deficiency On The Session Degradation.

The efficiency of dialysis equipment is extremely important in evaluation of adequacy of hemodialysis. Effective control of equipment and system status means coordinating operations and maintenance activities. Equipment deficiencies must be promptly identified for correction in the work control system. A process for post-maintenance testing should be in place to ensure that all operation of equipment is controlled by approved operating procedures and that appropriate maintenance and operations personnel are represented during the testing. As the equipment deficiency increases from 0 to 1, initially session degradation increases at higher rate than in the later part. According to the above graph, when 60% of deficiencies are present in the equipment and are critical to the session, the session has been degraded to the level of 0.93.

In order to improve system availability and reliability, various maintenance policies have been proposed based on different assumptions and considerations. System maintenance can be divided into three main categories preventive maintenance, predictive maintenance and reactive maintenance.

Preventive and predictive maintenance are the proactive strategies for avoiding equipment breakdowns. The preventive and predictive maintenance are very similar in concept with some differences in the criterion for determining the need for specific maintenance activities. Preventive maintenance represents all the actions performed in order to operate a system at an acceptable level of performance by providing systematic inspection, detection and prevention of incipient failures. Corrective maintenance represents all the actions performed as a result of failure to restore a system to acceptable performance level.

The actual overall equipment effectiveness (OEE) can be calculated from maintenance software as a function of the equipment breakdowns and the down time rate. The output of the maintenance software (OEE) can be linked with this model to calculate the overall dialysis session performance as a function of equipment efficiency (figure 6).

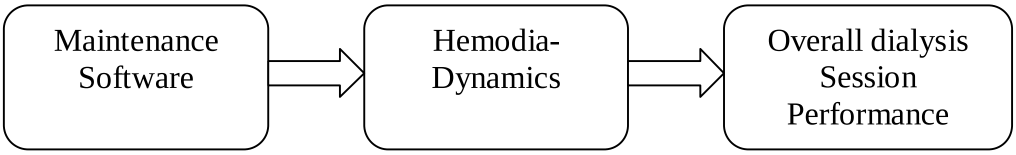

Figure 6 The Link Between Maintenance Software Model And Hemodiadynamics Model

The estimated average failure rate is the probability of a failure occurring during a stated period of time or cycle, and can be calculated as follows:

Breakdown rate = Equipment breakdowns/Test times (2)

The reciprocal of the breakdown rate is the average life (θ). For repairable items the average life is called the "mean-time-between failures" (MTBF). The "test times or cycles" in equation (2) is often a combination of the times that the failed piece of equipment or system was operational plus the times to repair. The Downtime which is referred to as "maintainability", can be measured in several ways:

- Active repair time includes only time spent in diagnosis and repair.
- Total downtime is the sum of times spent in active diagnosis and repair, delays waiting for parts, technical support and administrative work, and preventive maintenance.

OEE can be viewed as the percent of time that equipment would need to run at its maximum speed in order to attain the actual output of that tool or machine. Hence, the actual equipment effectiveness can be calculated as a function of maintainability and the equipment breakdown rate from the following equation:

Actual Effectiveness of Equipment = (100 – Breakdown rate – Down time rate * down time conversion unit) /100 (3)

The ratio of the actual equipment effectiveness to its theoretical maximum effectiveness determines the effect of the equipment effectiveness on dialysis adequacy.

b. Dialysis Session Performance Structure

Dialysis session performance subsystem determined when to take the session down for corrective actions and when to put it back into operations. There are various factors that govern this decision. These decision rules are decided based on the expert’s inputs. The dialysis session performance subsystem is shown in figure 7.

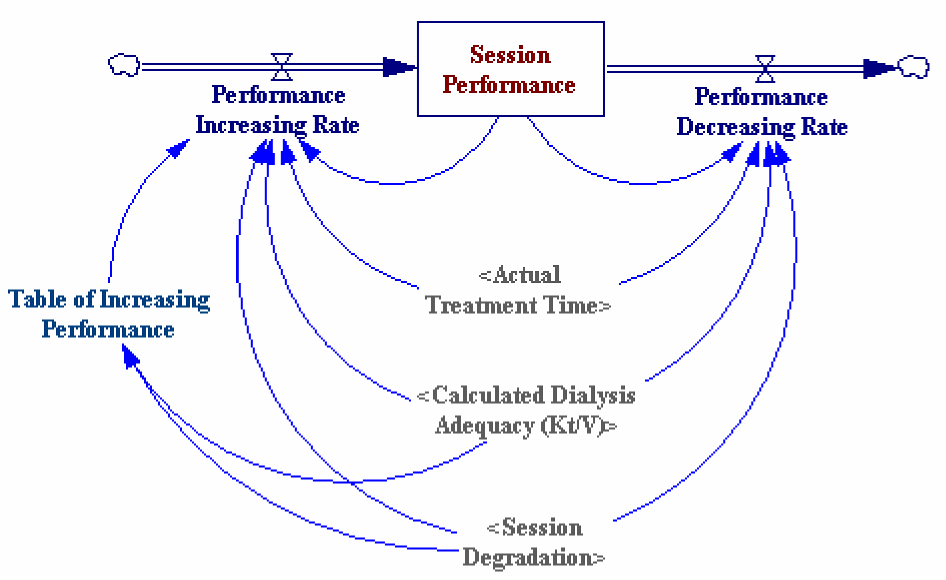

Figure 7 Dialysis Session Performance Subsystem

The session performance stock (Dimensionless) is fed into by session performance increasing rate (Dimensionless/Minute) and is depleted by session performance decreasing rate (Dimensionless/Minute). The session performance stock is an integral of the performance increasing rate less the performance decreasing rate.

Session Performance (t) = Session performance (0) + ∫ [performance increasing rate – performance decreasing rate] dt (4)

Session Performance (0) = 0

Performance of the session is measured using two variables; dialysis adequacy and session degradation. The following equations can be used to calculate the increasing and decreasing rates of session performance.

Performance Increasing Rate = IF THEN ELSE (Session Performance = 1, 0, IF THEN ELSE (Session Degradation <= 0.3: AND: "Calculated Dialysis Adequacy (Kt/V)" = 1.6, 0, Table of Increasing Performance/Actual Treatment Time)) (5)

Performance Decreasing Rate = IF THEN ELSE (Session Performance = 1, 0, IF THEN ELSE (Session Degradation >= 0.5: OR:" Calculated Dialysis Adequacy (Kt/V)" = 0, Session Performance/Actual Treatment Time, 0)) (6)

Session performance varies from 0 to 1. It can not take value greater than 1. If the additive impact of dialysis adequacy and session degradation in session performance is more than 1, its value is limited to 1 which indicated that the dialysis session reached the optimum performance. If the dialysis session degradation is more than 50 % or any interruption in dialysis adequacy occurs then the performance decreases until session degradation becomes no more than 30% and the dialysis adequacy increases again. If the dialysis adequacy reaches the optimum value of 1.6 and session degradation is less than 30 % this means that the session performance reached the desired performance level.

A linear multiple regression analysis was made through 164 patients to obtain an analytical expression capturing the effect of dialysis adequacy and session degradation on the overall dialysis performance. Regression analysis is used when to predict a continuous dependent variable from a number of independent variables. The curve fitting was done using Data Fit version 8.0.32. Figure 8 shows the model plot where X_1 represents the dialysis adequacy, X_2 represents the session degradation and Y represents the overall session performance.

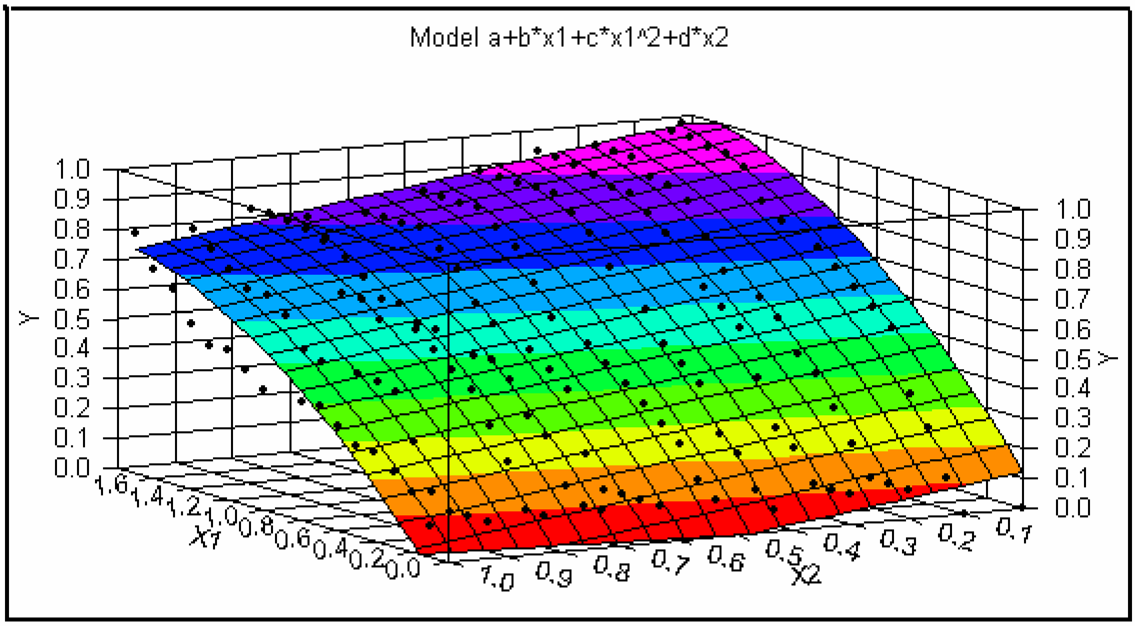

Figure 8 Effect Of Dialysis Adequacy And Session Degradation On Session Performance through 164 patients.

The regression analysis revealed that the R-squared, which denotes the percentage of variation in the dependent variable that can be explained by the independent variables is 0.9317, meaning that approximately 93% of the variability of effect of dialysis adequacy and session degradation on session performance is accounted for by the variables in the model. In this case, the adjusted R-squared indicates that about 93.04% of the variability of effect of dialysis adequacy and session degradation on session performance is accounted for by the model, even after taking into account the number of predictor variables in the model. The adjusted R-squared is a measure of how well the independent, or predictor, variables predict the dependent, or outcome, variable. The adjusted R-squared adjusts the R-square for the sample size and the number of variables in the regression model. Therefore, the adjusted R-square is a better comparison between models with different numbers of variables and different sample sizes. The adjusted R-squared can be computed as:

$$AdjustedR^2 = 1 - (1 - R^2)\frac{n-1}{n-k-1} \qquad (7)$$

Where, n = sample size and k = number of predictors.

The results of regression analysis are summarized in table 2:

Table 2. Regression Analysis Results for the Effect of Adequacy and Session Degradation on the Session Performance

Regression Coefficient	Coefficient Value	T-value
a	0.11313	6.10904
b	1.23131	18.49756
c	-0.19735	-7.96916
d	-0.23921	-12.73172

The regression coefficient of each X variable provides an estimate of its influence on Y, representing the amount the dependent variable Y changes when the corresponding independent variables change 1 unit. The variable a is the constant, where the regression line intercepts the y axis, representing the amount the dependent Y will be when all the independent variables are 0. T-tests are used to assess the significance of individual X variable coefficients, specifically testing the null hypothesis that the regression coefficient is zero. A common rule of thumb is to drop from the equation all variables not significant at the 0.05 level or better. The value of standard error of estimate is 0.07513. The standard error of estimate indicates the accuracy of a prediction model and can be computed by the equation of the standard deviation of the error variable. The smaller the standard error of estimate, the better the prediction. Hence, the overall equation to describe the relationship is:

Effect of adequacy and session degradation on session performance = 0.11313 + 1.23131 * "Calculated Dialysis Adequacy (Kt/V)" – 0.19735 * "Calculated Dialysis Adequacy (Kt/V)" ^2 – 0.23921 * Session Degradation (8)

III. Results and Behaviors

Various runs were conducted and the results were relatively compared against each other. These results were also thoroughly validated by the subject matter experts. The behaviors observed result from the interactions of numerous feedback loops present in the structure. Sometimes it might be difficult to attribute the observed behavior to any particular feedback loop. Partial simulation runs were conducted to ensure the appropriateness of the formulation. The values of exogenous variables, to certain extent, determine the dominance of feedback loops which ultimately result into specific system behavior. These values can be changed to observe their impact on the system's behavior.

Exponential growth arises from positive (self-reinforcing) feedback. Figure 9 shows the generic structure responsible for exponential growth. Increase in state of the system increases the net increase rate which in turn increases the state of the system.

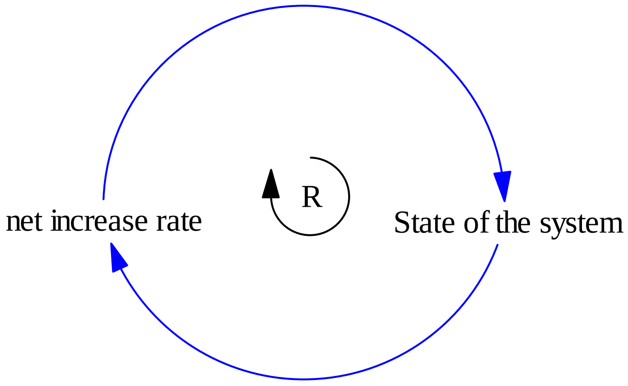

Figure 9 Positive (Self Reinforcing) Loop

Loops R1 and R2 explain the exponential growth mentioned above exhibit the exponential increase in session performance. To show the behavior of the intradialytic model, partial simulation runs were conducted. This partial simulation means that the patient receives the dialysis treatment. Hence, the performance of the dialysis session is measured using two variables; dialysis adequacy and session degradation. The resulting behavior is exponential growth in session performance as shown in figure 10.

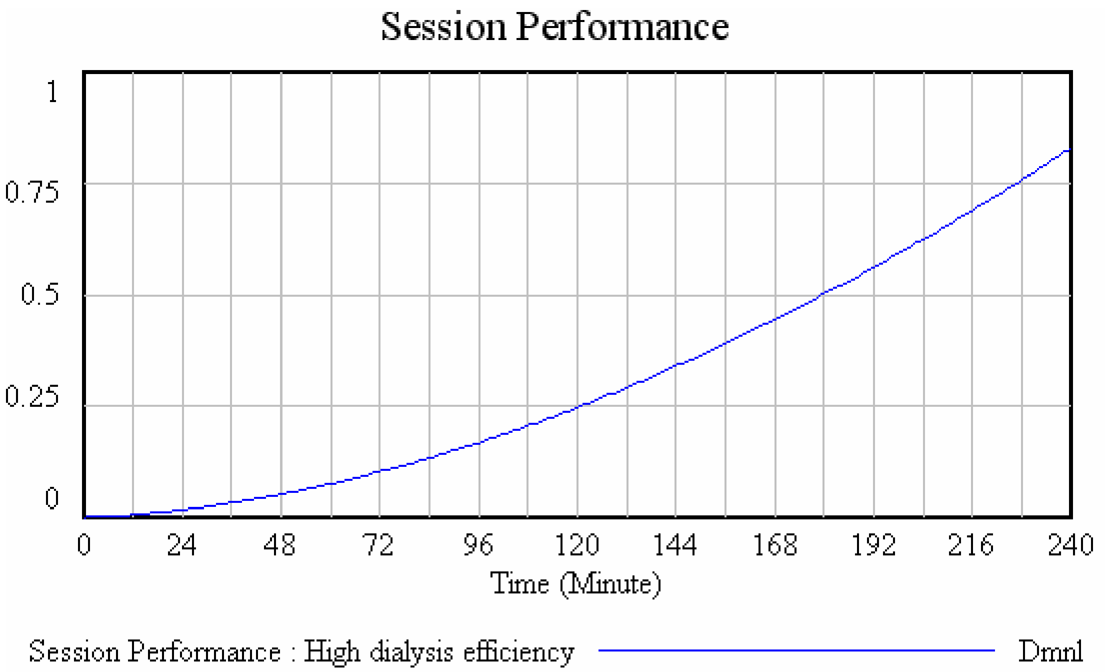

Figure 10 Partial Simulations – Session Performance

A. Testing of Dynamic Hypothesis: Dialysis Performance Drivers

The hypotheses were tested at various levels of dialysis adequacy and session degradation. The first simulation was run at a dialysis adequacy level being less than the recommendation for a minimum dialysis dose Kt/V of 1.2 and at high level of session degradation (i.e. > 40 % due to high level of complications and low level of equipment effectiveness).

The second simulation was run at a dialysis adequacy level being equal to the minimum dialysis dose Kt/V of 1.2 and at critical level of session degradation (i.e. = 40 % due to medium level of complications and equipment effectiveness). The third simulation was run at a dialysis adequacy level being greater than the minimum dialysis dose Kt/V of 1.2 and at and at low level of session degradation (i.e. < 40 % due to low level of complications and high level of equipment effectiveness). The results are shown in Figure 11 and 12. It is observed that the overall dialysis session performance increases as the amount of dialysis dose is increased. The results also indicate that low session degradation levels increases the dialysis session performance as the probability of complications decreases and the effectiveness of equipment increases. The results demonstrate that these hypotheses are shown for the current structure of the model.

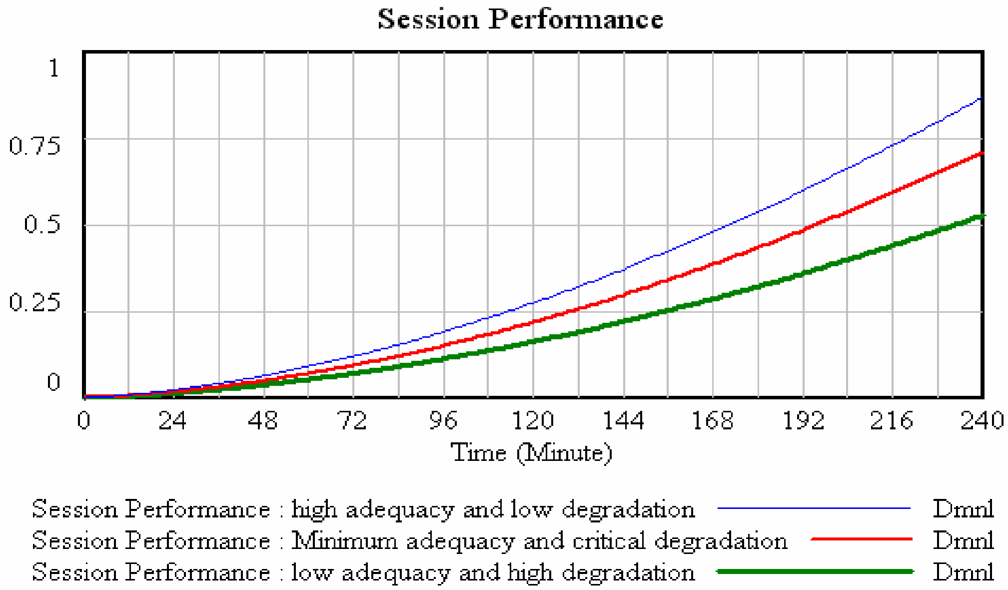

Figure 11 Dialysis Session Performance at various levels Of Kt/V and Session degradation

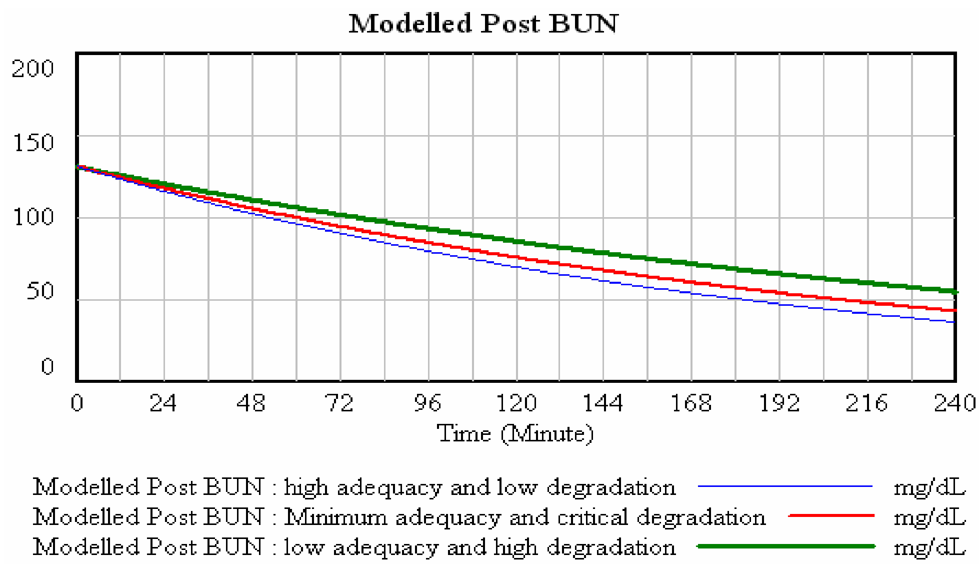

Figure 12 Modeled Post BUN at Various Levels of Kt/V And Session Degradation

B. Sensitivity analysis

Sensitivity analysis is used to determine how "sensitive" a model is to changes in the value of the parameters of the model and to changes in the structure of the model. Parameter sensitivity is usually performed as a series of tests in which the modeler sets different parameter values to see how a change in the parameter causes a change in the dynamic behavior of the stocks. By showing how the model behavior responds to changes in parameter values, sensitivity analysis is a useful tool in model building as well as in model evaluation. Sensitivity analysis helps to build confidence in the model by studying the uncertainties that are often associated with parameters in models. Many parameters in system dynamics models represent quantities that are very difficult, or even impossible to measure to a great deal of accuracy in the real world. Also, some parameter values change in the real world. Sensitivity analysis indicates what level of accuracy is necessary for a parameter to make the model sufficiently useful and valid.

Five tests were performed as follows where the model yielded an expected behavior in all tests. (1) Effect of equipment effectiveness on the intradialytic complications, (2) Effect of equipment effectiveness on session degradation, (3) Effect of equipment effectiveness on dialysis dose Kt/V, (4) Effect of equipment effectiveness on post-Blood Urea Nitrogen (BUN) (5) Effect of equipment effectiveness on the overall session performance. The results of these tests were simulated with three sets of key parameter combinations, namely, (1) New Equipment that no maintenance procedures were performed, (2) High efficiency equipment with low number of working hours and regular maintenance procedures, and (3) Low efficiency equipment with high number of working hours and accrued maintenance procedures.

1. Effect Of Equipment Effectiveness On The Intradialytic Complications

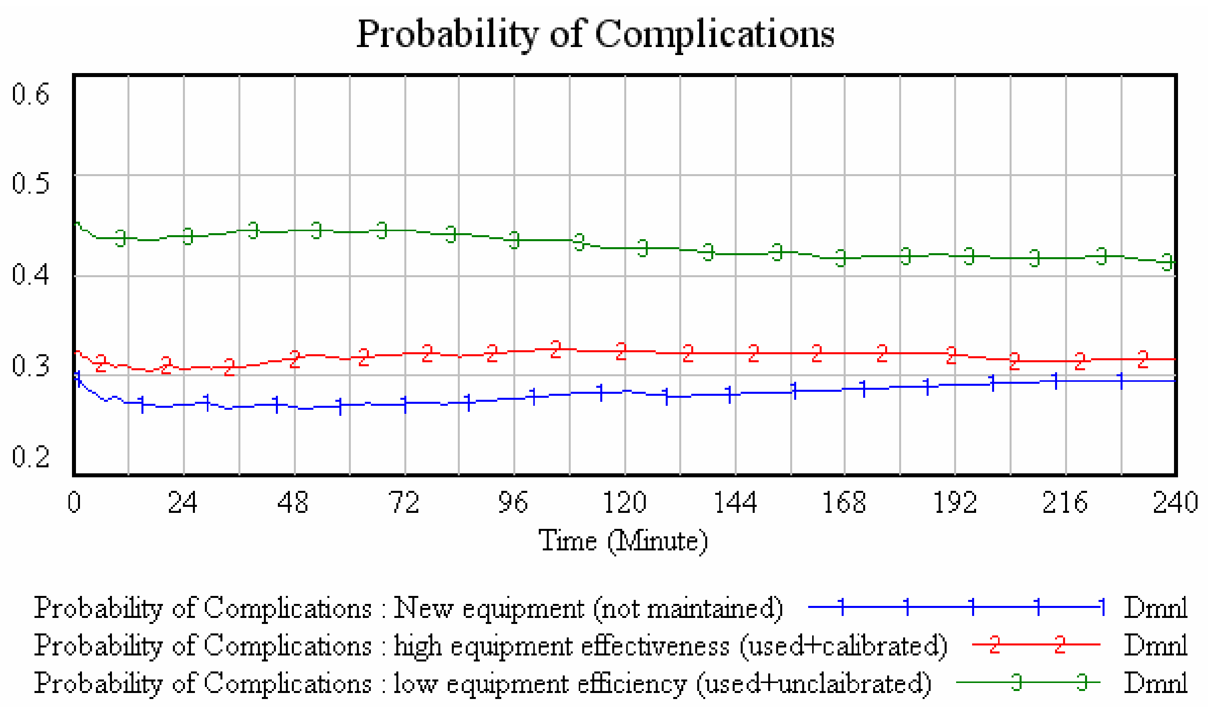

Figure 13 Effect Of Equipment Effectiveness On The Intradialytic Complications

It is noted from figure 13 that new equipments without any defects and used equipments with regular and effective maintenance procedures doesn't enhance the probability of intradialytic complications among hemodialysis patients. The experimental study that was applied on 134 hemodialysis patients showed that accrued maintenance programs increase the probability of complications by about 45 % among hemodialysis patients due to uncalibrated blood and dialysate pumps so that the proper setting can't be delivered to the patient from the machine.

(2) Effect of equipment effectiveness on session degradation

Session degradation is defined as the session failure due to intradialytic complications and equipment deficiency. It is a dimensionless variable measured using a relative scale (varying from 0 to 1; 0 corresponds to total success and 1 corresponds to total failure). Figure 14 shows the effect of equipment effectiveness on session degradation. The simulation result revealed that low equipment efficiency due to deferred maintenance procedures increases the hemodialysis session degradation to about 56 % and may causes severe problems and complications to the patients. The experimental study revealed that there is no session degradation was noted due to new hemodialysis equipments but the amount of session degradation was due to the complications that were happened to patients during session.

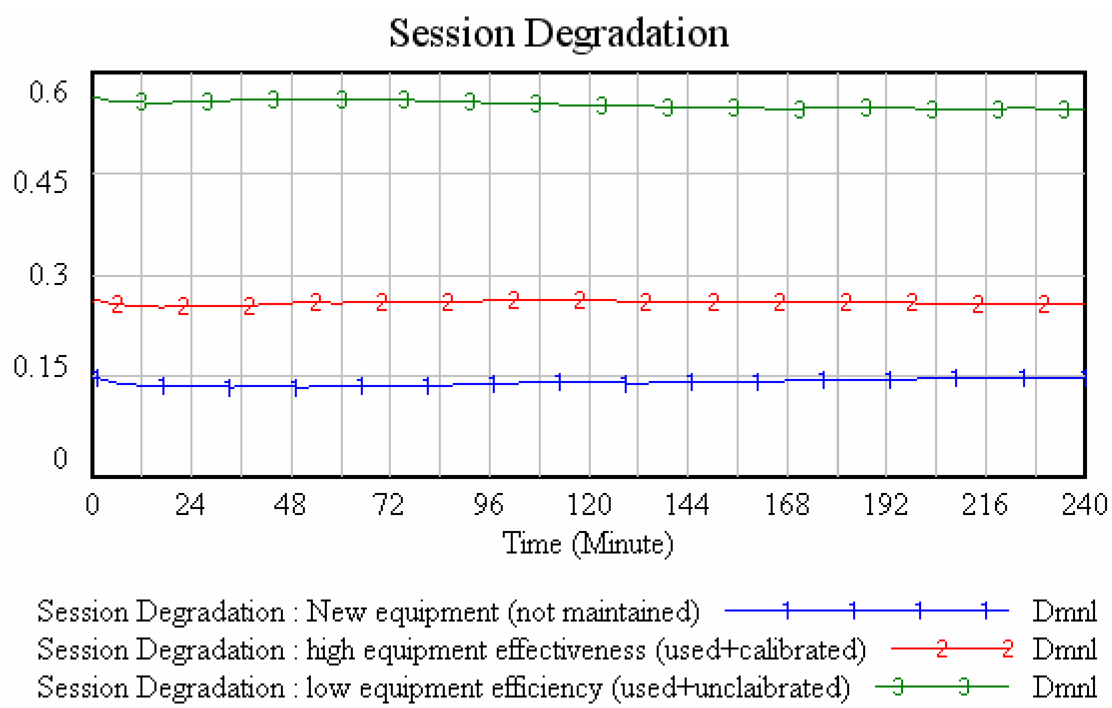

Figure 14 Effect Of Equipment Effectiveness On session degradation

(3) Effect of equipment effectiveness on dialysis dose Kt/V & (4) Effect of equipment effectiveness on post-blood urea nitrogen (BUN)

To evaluate the effect of equipment effectiveness on dialysis adequacy, the 134 patients were grouped to:

- 22 patients (16.42%) dialyzed with new hemodialysis equipments
- 102 patients (76.12%) dialyzed with used and calibrated equipments
- 10 patients (7.46%) dialyzed with used and uncalibrated equipments.

It is concluded that increasing the equipment effectiveness is associated with a statistically significant increase in Kt/V and decreasing in post-blood urea nitrogen (BUN). Hemodialysis with calibrated equipments should be considered in selected patients not achieving adequacy to optimize blood, dialysate and ultrafiltration flow rates. The statistical analysis revealed also that there was a statistically significant increase in the dialysis adequacy Kt/V and urea reduction ration (URR) as the equipment efficiency increases from low efficiency equipment to high efficiency equipment. It is noted from figure 15 that by using the calibrated hemodialysis equipments with regular maintenance procedures the dialysis dose Kt/V increases to the desired value of 1.3. The Kt/V values for those patients dialyzed with low efficiency and uncalibrated equipments are less than 1 which is inadequate dialysis dose.

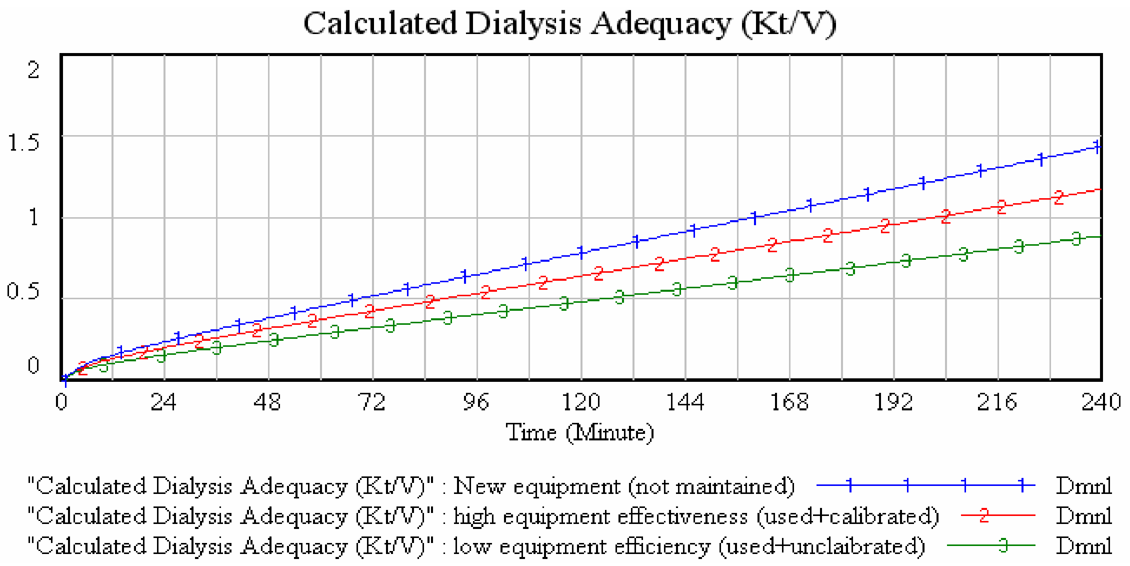

Figure 15 Effect of equipment effectiveness on dialysis dose Kt/V

The urea reduction ratio (URR) for those patients dialyzed with maintained and calibrated equipments also increases due to the decrease in the blood urea nitrogen (BUN). It is noted from figure 16 that use of low-efficiency equipments can result in a low reduction in the post-BUN.

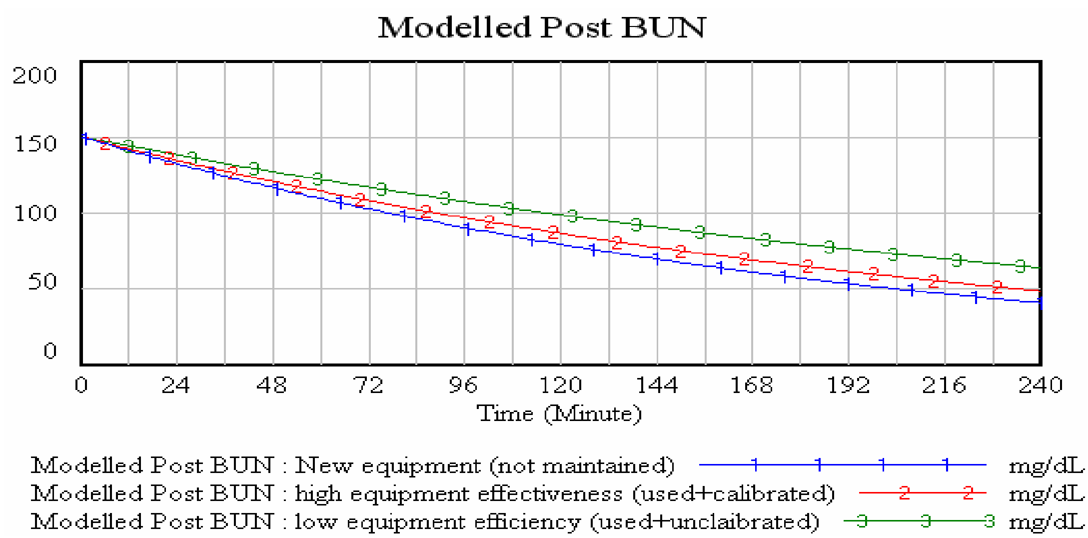

Figure 16 Effect of equipment effectiveness on post-Blood Urea Nitrogen (BUN)

The statistical analysis demonstrated that there was a statistically significant increase in Kt/V by about 52.93% (from 0.82 with low efficiency equipment to 1.254 with high efficiency equipment) The URR increases also by about 23.66% from 56.50% to 69.87% when switching from low efficiency dialysis equipment to high efficiency equipment.

(5) Effect of equipment effectiveness on the overall session performance

The overall hemodialysis session performance increases by about 34% from 55.94% when the patients dialyzed with low efficiency and uncalibrated equipments to 74.96% when patients dialyzed with calibrated and high efficiency equipment. The hemodialysis session performance increases by about 17.09% when switching dialysis from used and calibrated equipments to new equipments. The effect of equipment efficiency on session performance is shown in figure 17.

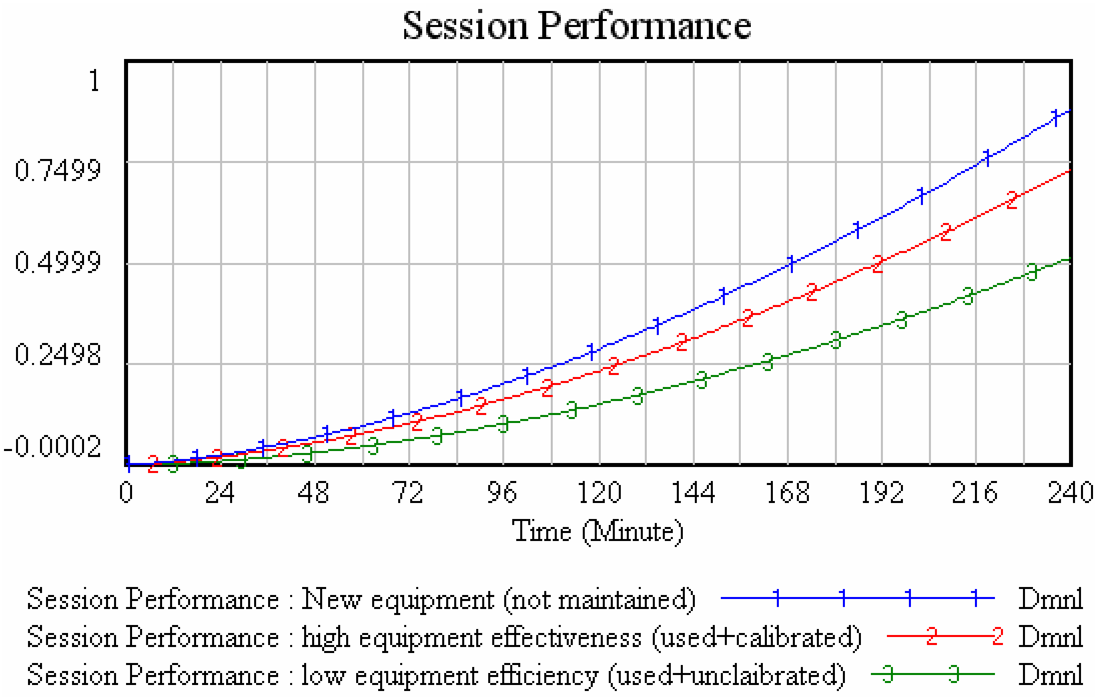

Figure 17 Effect of equipment effectiveness on the overall session performance

IV. DISCUSSION

An issue of increasing importance to all nephrologists is the correct assessment of dialysis performance. Recent studies have shown how efficient the use of urea kinetic modeling (UKM) is in the quantification and monitoring of dialysis, and also in predicting patient morbidity and mortality. On this basis, the overall goal of this research was to build a system dynamics model to quantify the hemodialysis session performance from systems perspective. No successful results have been reported on this topic to date. We were able to accomplish the research goal. The system dynamics model was developed using Vensim DSS 4.0a. The model was structured based on the inputs from the experts in the field of nephrology. The model was extensively tested and the results were validated by the experts so that we can conclude that this model has a high degree of statistical significance. It should be noted that the base case values used for simulation are a real data measured from dialysis patients Using this system dynamics model, a significant improvement in dialysis performance was achieved by highlighting factors which may alter the delivered dose and may lead to session degradation. This model represents significant advances over previous urea kinetic models. In short, the model developed during the course of this research makes possible the accurate reagentless monitoring of dialysis performance over time where previous models have failed. The dynamic hypotheses stated in section III.A were tested using the system dynamics model developed using Vensim DSS 4.0 by varying parameters and observing the changes in the subsequent results from the simulation. The primary and secondary hypotheses depend on dialysis session improvement due to the increase in dialysis adequacy and the reduction of session degradation. These hypotheses were tested at various levels of dialysis adequacy and session degradation.

The simulation results support the stated dynamic hypothesis and demonstrated that these hypotheses are shown for the current structure of the model. The simulation shows that the effective and regular maintenance procedures have a different impact on the behavior of the dialysis system. By linking the maintenance software with hemodialysis system dynamics model it was noted that the required preventive maintenance should be completed during the preventive maintenance cycle to ensure that the dialysis machine is accurate and well calibrated. Deferred maintenance will leave the machine in partially degraded state which may further degrade the system at higher rate and hence will decrease the performance of the system over the entire operational phase. The preventive maintenance interval should be determined based on the maintainability factors such as mean preventive maintenance time, mean corrective maintenance time and maintenance man-hours required per operational cycle.

V. CONCLUSION

Dialysis quality is a complex and evolutionary concept that has to be viewed in a quality assurance process to improve outcomes of end stage renal disease (ESRD) patients. To simplify this assessment it is very important that dialysis machines have to be maintained on a regular basis. The necessary amount of regular maintenance can be done by the maintenance department. The overall goal of the maintenance procedures is to raise the overall equipment effectiveness. Dialysis machines with a high maintenance standard are able to deliver proper settings to the patient with less or no failures. Maintenance has become one of the most expedient approaches to guarantee high machine dependability.

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Appendix A The Overall Stock And Flow Diagram Of Hemodiadynamics