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Automatic Control of Electrodes in Lithotripsy Machine

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Abstract

Extracorporeal shock wave lithotripsy (ESWL) employs high-energy shock waves that propagate through the body and focus on the stone to break it into small grains, which travel out of the body along with the urine. The distance between lithotripsy long-life electrodes tends to vary after every session. This variation causes an associated pain for the patient, and hence the need for re-calibration and adjustment of the distance. Both manual calibration and adjusting procedure are time wasting, inaccurate, and must be performed by an expert operator.

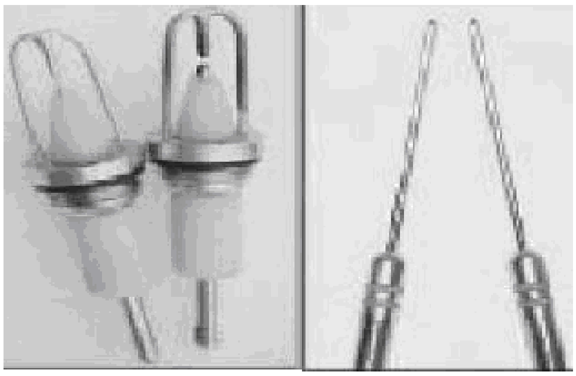
In this paper, a mathematical model has been developed to predict the number of shocks needed for every patient, depending on input information regarding his age, stone size, and location. An automatic adjustment procedure for the distance between electrodes, utilizing a proportional integral derivative controller, is also proposed in order to increase treatment effectiveness and to reduce patient pain. This also enables better planning of treatment and allows the possibility for any operator to use, and thus resulting in a better utilization of apparatus. Results from trials in a hospital were adequate, and the experimental data matched those predicted by the model.

Keywords: Solar Still; Lithotripsy; Kidney Stones; Shock-Waves.

1. Introduction

Extracorporeal Shock Wave Lithotripsy is a technique for destructing stones in the kidney and ureter into smaller particles that can be disposed of by the urine system, and this spares the patient the agony of surgery. This technique still imposes some pain and problem in the planning procedure [1]. Several researchers have proposed models to reduce the amount of pain and wasted time accompanied this process [2, 3]. There are two main types of lithotripsy electrodes which are used in hospitals and clinics: the first type is the disposable electrode shown in Figure 1a, which has the function of discharging the electrical shock wave, and this type is used for only one session. The other type is the adjustable electrode, shown in Figure 1b and known as the long life electrode where it can be used up to 50 sessions. Both electrodes could be either flat or conical depending on the electrode shape. In this paper, the second type has been investigated where a new method for automatically adjusting and controlling the distance or the gap between the electrodes is presented (Refer to Figure 1).

At present, the non-disposable long life lithotripsy electrode gap is adjusted manually by the doctor or the physician where it can be performed by placing a calibrated and a well-known thickness of metal sheet directly in the gap between the electrodes heads and manually adjusting the venire to the desired thickness [4]. This process is time consuming and exposes the patient to more pain than necessary. The main objective of this research is to introduce a scientific and a reliable way to automatically control and adjust the long life electrodes. This should increase the treatment effectiveness and further reduce patient's pain.



(a) (b)

Figure 1. (a) Disposable Electrodes, and, (b) None disposable Electrodes [5].

2. Treatment Process

The process of removing a stone from the kidney or from the ureter without the need for an open surgical technique is known as lithotripsy, which is a non-invasive surgical technique. The technique involves disintegration of the stone in vivo, so that it can pass through the urinary tract in the form of small particles, the passage of which doesn't result in sever discomfort or disability. The treatment process can be planned ahead depending on patient weight, sex, and type of stone [2, 3]. This planning

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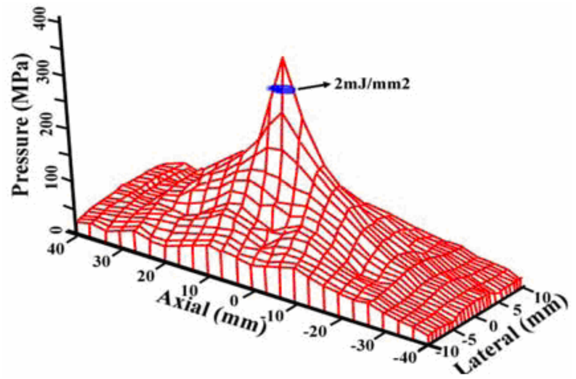
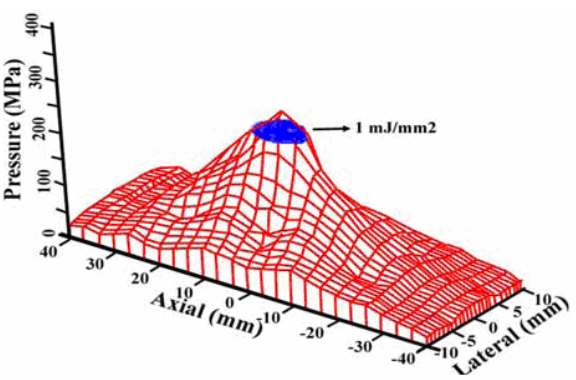
will indicate more accurately the times when the automatic adjustment should take place [4].

In percutaneous lithotripsy, a probe is guided under X-ray fluoroscopy through a small incision into the location of the kidney stone. Mechanical shock waves are produced at the tips of the probe by a controlled electric-discharge (spark), or the probe contains an ultrasonic transducer that produces ultrasonic waves. Each of these forms of energy is used to break up the kidney stone, so that it can be withdrawn in pieces through the probe guide element or can be allowed to pass through the urinary tract.

Extracorporeal shock wave lithotripsy generates high-pressure waves outside the body which can be focused at a specific site with in the body called the Focal Point (F_2). This focal point is important and is needed throughout the treatment process in order to concentrate and direct the shock wave energy on the stone, so that a maximum fragmentation can occur to the stone with minimum pain and discomfort to the patient [6]. The variation of the size of the focal point results in variation to the energy density [7], and hence the total energy being delivered to the desired treatment area, as shown in Figure 2a and 2b.



(a)



(b)

Figure 2. (a) High energy density for a fine focal. [7], (b) Same total energy distributed over a larger focal point. [7]

Many mechanical shock waves are produced at one focus of an ellipsoidal reflector such that these waves converge to another focal point several centimetres away from the reflector. The reflector and the patient are submerged in demineralised, degassed water in such a way enabling the patient to move until the stone is located at the focal point of the shock wave. This positioning of the patient is critical, and a biplane X-ray system is used to establish the position of the stone at the focal point as well as to monitor its disintegration.

A high-voltage pulse (approximately 20 kV) is applied to the spark gap, and the discharge produces a shock wave that propagates through the water to the focal point. The patient is placed on a gantry support that can be precisely positioned as the operator observes the stone on the biplane X-ray monitors. Once the patient is approximately positioned, multiple-shock waves are generated by multiple discharges across the spark gap. Up to 2000 shock waves may be necessary to reduce kidney stone down to one to two millimetre fragments that can pass through the urinary tract. With this treatment, most patients are able to resume full activity after two days. This considerably reduce the needed time than surgical treatment by lithotomy would entail. Although the apparatus is complex and expensive to purchase and operate, the overall savings for the patient and the health-delivery system are clear [1, 8].

2.1. Energy and Number of Shocks

Depending on many factors, doctors can determine the appropriate energy of each shock (kV) and the corresponding number of shocks, which can be used as the input to the lithotripsy instrument. From 2^K factorial design, the most significant factors on ESWL outcome are related to the stone and to the patient. Doctors depend on these factors to determine the appropriate energy of each shock (kV) and the corresponding number of shocks. These factors are:

- Factors related to the patient such as age and condition of patient.
- Factors related to the stone such as, diameter, composition, location, and number of stones.

The stones may have different shapes and different diameters. Figure 3 illustrates some of the stones found in human bodies. Generally, stones with diameter below 2cm can be successfully treated with ESWL. On the other hand, specialists recommend that stones with greater diameter should not be treated with the ESWL. A stone located in the kidney is known as renal calculi while the stone located in the ureter is known as ureteric calculi.

2.2. Collecting Data and Analysis

Several data were collected from various clinical centres taking in mind the factors mentioned earlier [9, 10, and 11]. Tables 1 ,2, and 3 illustrate these data. It is obvious that the location of the stone, its size, and age effect the treatment process in terms of number of shocks and the energy given in (kilo Volt; kV). Design Ease software package [12] and statistical analysis [13, 14, 15, and 16] have been used where factors such as patient age, stone location, and stone diameter are considered as input variables while the number of shocks is considered as the output.

The results with all factors and coefficients are illustrated in Table 4-a and Table 4-b:

From these tables, a relationship can be derived between the patient age (A), stone position (B), stone diameter (C), and the number of shocks (N) given to the patient as illustrated in Equation 1 below:

$$N = 2350 + 225*A + 725*B + 1075*C + 100*A*B + 100*A*C + 350*B*C + 75*A*B*C \quad (1)$$

It can be noted that:

1. Sum source squares values are as follows ***C>B and B>B*C and B*C>A***
2. Coefficients values are as follows ***C>B and B>B*C and B*C>A***
3. The most significant factors affecting ESWL outcomes are: stone diameter, stone position (or location), and ***position-diameter*** (location-diameter), and patient age. So we choose these factors for the next step of analysis. This is shown in Figure 3 and Figure 4.

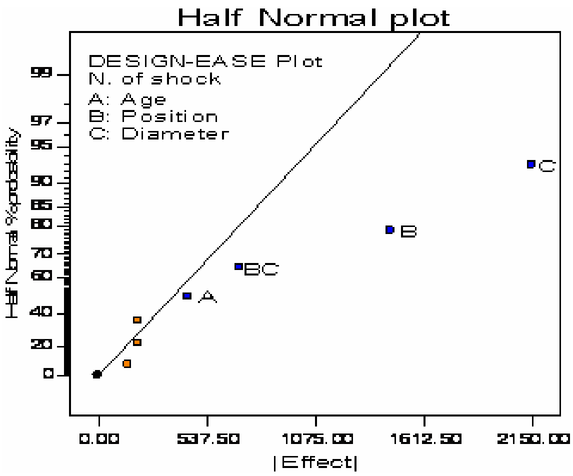


Figure 3. Half normal plot.

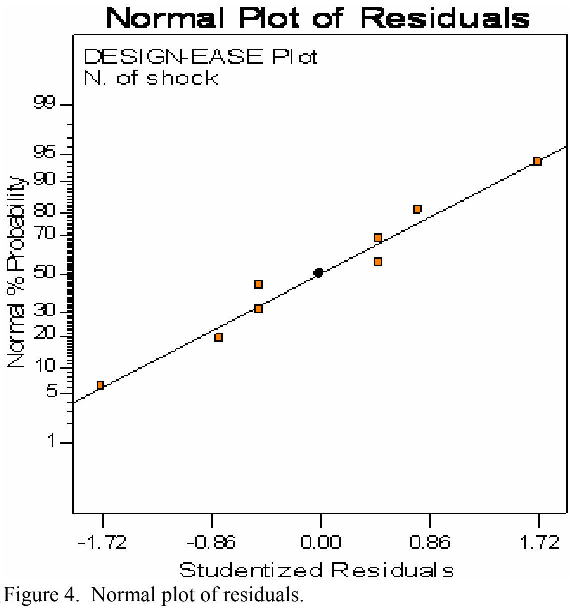


Figure 4. Normal plot of residuals.

Now we will conduct analysis of variance the selected factorial design.

Through close inspection of Table 5-a, Table 5-b and Table 5c, it could be noticed that:

I. The Model F-value of 54.27 implies that the model is significant, and there is only a 0.39% chance that a "Model F-Value" this large could occur due to noise.

II. Values of "Prob > F" less than 0.0500 indicate model terms are significant, in this case B, C, BC, and A are significant model terms, values greater than 0.1000 indicate the model terms are not significant.

III. The 'pred R-squared' of 0.9031 is in reasonable agreement with the 'Adj R squared' of 0.9682.

IV. Adeq precision' measures the signal to noise ratio. A ratio greater than 4 is desirable, and the ratio of our design is 19.597 indicating an adequate signal.

This leads to the Equation 2 of the number of shocks (N) in terms of Coded Factors:

$$Number\ \ of\ \ Shocks = 2350\ +\ 225*A\ +\ 725*B\ +\ 1075*C\ +\ 350*B*C \qquad (2)$$

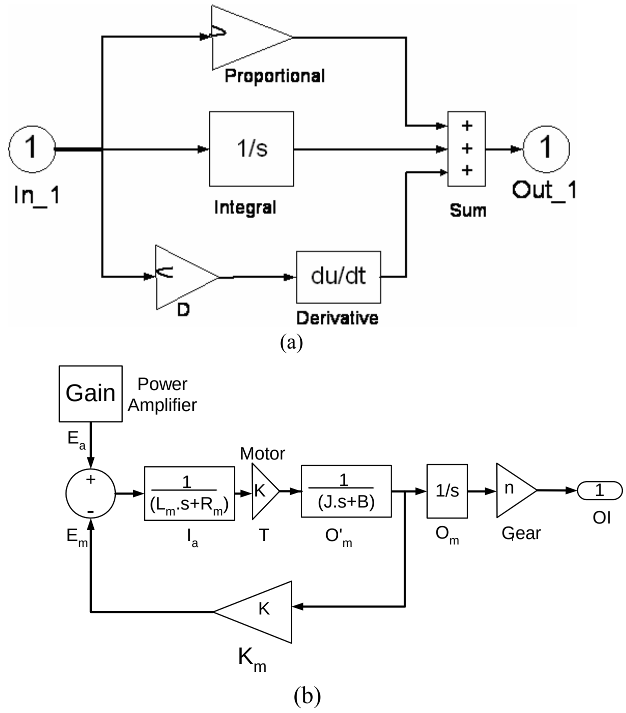


Figure 5. (a) Block diagram of PID controller, (b) Block diagram of plant (power amplifier, stepper motor, and gear).

Table 1. Data regarding patient age, location and number of shocks [9]

Patient Age (Years)	Stone Location	Stone Diameter (mm)	Response1 Run No. of Shocks per Session	No. of Sessions
18	Kidney	2	800	1
90	Kidney	2	1000	1
18	Ureter	2	1500	1
90	Ureter	2	1800	1
18	Kidney	20	2200	2
90	Kidney	20	2500	2
18	Ureter	20	4000	2
90	Ureter	20	5000	2

The following conclusions can be derived from the previous equations and analysis:

1. The numerical estimates of the effect indicate that the effect of stone diameter (C) is large and has a positive direction (increasing C increases number of shock), since

changing stone diameter from low (2 mm) to high (20 mm) changes the number of shocks by 1075 shocks.

Table 2. Data regarding patient age, location and number of shocks [10]

Patient Age (Years)	Stone Location	Stone Diameter (mm)	Response1 Run No. of Shocks per Session	No. of Sessions
30	Kidney	5	1200-1500	1
30	Ureter	5	2000-2200	1
30	Kidney	10	1800-2000	1
30	Ureter	10	2000-2500	1
30	Kidney	15	≈ 2200	2
30	Ureter	15	≈ 4000	2
30	Kidney	20	≈ 2200	2
30	Ureter	20	≈ 5000	2

2. The numerical estimates of the effect indicate that the effect of stone position (B) is large and has a positive direction (increasing B increases number of shock), since changing stone position from low (kidney) to high (ureter) changes the number of shocks by 725 shocks.
3. The numerical estimates of the effect indicate that the effect of position-diameter (B*C) is large and has a positive direction (increasing B*C increases number of shock), since changing stone position-diameter from low (kidney-2mm) to high (ureter-20mm) changes the number of shocks by 350 shocks.
4. The numerical estimates of the effect indicate that the effect of patient age (A) is large and has a positive direction (increasing A increases number of shock), since changing patient age from low (18 years) to high (90 years) changes the number of shocks by 225 shocks.
5. The most significant factors are stone diameter and its location while the patient age has less effect on the number of shocks given to the patient.
6. This result agrees with the practical specimens collected from various medical centres as shown earlier.

The best method used to study the factors that vary together is the factorial design method, where the most important benefits from the process are that any operator can treat the patient without the need for high experience to determine number of shocks and energy of each case.

3. Model Construction

From 2^k factorial design the most significant factors affecting ESWL outcome are patient age, stone position, age-and-position interaction, and stone size. In LABVIEW software, the patient age and the stone size are selected

Table 3. Data information regarding patient age, location and number of shocks [11]

Patient Age (Years)	***Stone Location***	**Stone Diameter (mm)**	**Response1 Run No. of Shocks per Session**	**No. of Sessions**	**kV**
10	Kidney	5	2000	1	12
10	Ureter	5	2000	1	12
10	Kidney	10	2000	1	12
10	Ureter	10	2000	1	12
10	Kidney	15	2000	2	12
10	Ureter	15	2000	2	12
10	Kidney	20	2000	2-3	12
10	Ureter	20	2000	2-3	12
10	Kidney	25	2000	3-4	12
10	Ureter	25	2000	3-4	12
10	Kidney	30	2000	> 5	12
10	Ureter	30	2000	> 5	12
20	Kidney	5	4000	1	18
20	Ureter	5	6000	1	18-20
20	Kidney	10	4000	1	18
20	Ureter	10	6000	1	18-20
20	Kidney	15	4000	2	18
20	Ureter	15	6000	2	18-20
20	Kidney	20	4000	2	18
20	Ureter	20	6000	2	18-20
20	Kidney	25	4000	3	18
20	Ureter	25	6000	3	18-20
20	Kidney	30	4000	> 5	18
20	Ureter	30	4000	> 5	18-20

Table 4a.Analysis of variance for all factors.

Model	**Sum of Source Squares**	**DF**	**Mean Square**
	1.504E+7	7	2.149E+6
A	4.050E+5	1	4.050E+5
B	4.050E+6	1	4.205E+6
C	9.245E+6	1	9.245E+6
A*B	80000.00	1	80000.0
A*C	80000.00	1	80000.0
B*C	9.800E+5	1	9.800E+5
A*B*C	45000.00	1	45000.0

Table 4b.Factor estimates and their coefficient.

Factor Estimate	**Coefficient**
Intercept	2350.00
A - Age	225.00
B - Position	725.00
C - Diameter	1075.00
A*B	100.00
A*C	100.00
B*C	350.00
A*B*C	75.00

Table 5a.Analysis of variance for selected factorial design

Model	Sum of Squares	DF	Mean Square	F Value	Prob > F
Intercept	1.484E+007	4	3.709E+006	54.27	0.0039
A	*4.050E+005*	1	*4.050E+005*	*5.93*	*0.0930*
B	*4.205E+006*	1	*4.205E+006*	*61.54*	*0.0043*
C	*9.245E+006*	1	*9.245E+006*	*135.29*	*0.0014*
BC	*9.800E+005*	1	*9.800E+005*	*14.34*	0.0323

Table 5b. data analysis.

Std. Dev	261.41
Mean	2350.00
R-Squared	0.9864
Adj R-Squared	0.9682
Pred R-Squared	0.9031
Adeq Precision	19.597

Table 5c. Standard error of data

Coefficient Factor	Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF
Intercept	02350.0	1	92.42	2055.87	2644.13	1.00
A-Age	225.00	1	92.42	-69.13	519.13	1.00
B-Position	725.00	1	92.42	430.87	1019.13	1.00
C-Diameter	1075.00	1	92.42	780.87	1369.13	1.00
BC	350.00	1	92.42	55.87	644.13	1.00

To be the inputs while the number of shocks is the output. The Model was obtained using Mathcad as follows:

MAD=	18	2	VN=	600
	26	4		1000
	34	6		1400
	42	8		2000
	50	10		2200
	58	12		2200
	64	14		2500
	72	16		3500
	80	18		4000
	90	20		4000
K=1	Span =0.75			
The answer of the regress are the coefficients:				
3				
3				
Regress(MAD,Vn, K)=	1	K		
	-13.41	a_1		
	-315.513	a_2		
	-546.667	a_0		
The equation:				
Number of Shocks = N = 546.667-31041*A+315.513*D				
Where, A is the patient age, D is the stone diameter				

4. Proportional Integral Derivative (PID) Controller

The distance between the two electrodes has to be automatically adjusted using a closed loop control system. This process will keep the focal point F_2 in the optimal position to minimize the pain and discomfort to the patient. An automatic control model of distance between the electrodes is simulated, using MATLAB, and SIMULINK was used to visualize the performance of the controller; the design is simulated as a closed loop control system containing controller, plant, and sensor unit.

The PID controller combines the proportional (P), the integral (I), and the differential component (D) as Figure 5a and Figure 5b show. The manipulated value $\boldsymbol{y}$ is given by Equation 2 and further simplified into Equation 3 [17, 18, and 19]:

$$y = K_P \,.\, x_d + \frac{1}{T_i}\int x_d \,.\, dt + K_d \,.\, \frac{d\,x_d}{dt} \tag{3}$$

$$y = K_P\left(x_d + \frac{1}{T_r}\int x_d \,.\, dt + T_d \,.\, \frac{d\,x_d}{dt}\right) \tag{4}$$

Where
y = Controller output
K_p = Proportional gain.
T_i = Integral time.
K_d = Derivative action coefficient.
T_r = $K_p T_i$ Reset time which is the period by which the PI controller is faster than the I Controller.
T_d = K_d/K_p the time needed to get the wanted manipulated variables using D component earlier than when using the PI controller.

Stepper motors are low-cost solution for position control and inherently high torque/position gain resulting in excellent holding torque. The electrical torque acts to increase rotational speed (ω), while the mechanical torque acts to slow it. The net accelerating torque in the machine:

Torque=moment of inertiax accleration

$$T_{net} = J \times \alpha \tag{5}$$

$$T_{net} = J \times \left(\frac{d\omega}{dt} \right) \tag{6}$$

$$T_{net} = J \times \left(\frac{d^2(\theta)}{dt^2} \right) \tag{7}$$

Where:
T_{net} : net accelerating torque in machine(N.m.s)
J : moment of inertia for the machine(N.m.s^2).
α : rotational acceleration (rad/sec^2).
θ : phase angle of a rotating machine(rad) .
Assuming a constant field current and a constant flux Ø,

$$e_m(t) = K \,.\, \Phi . \frac{d(\theta)}{dt} = K_m . \frac{d(\theta)}{dt} \tag{8}$$

where:
$e_m(t)$ is the back electromotive force (V).
K is the motor parameter
K_m is a function of the permeability of magnetic material.
Then, by *Laplace* transform;

$$\frac{E_m(s)}{\theta(s)} = K_m(s) \tag{9}$$

The armature current is related to the input voltage applied to the armature as

$$E_a(s) = (R_m + L_m .s) . I_a(s) + E_m(s) \tag{10}$$

$$G_1(s) = \frac{I_a(s)}{\{\, E_a(s) - E_m(s) \,\}} = \frac{1}{(R_m + L_m .s)} \tag{11}$$

Where:
I_a is the motor armature current
E_a is the motor input voltage
The armature current would be:

$$I_a(s) = \frac{E_a(s) - E_m(s)}{R_m + L_m .s} \tag{12}$$

The torque developed by the motor is assumed to be related linearly to Ø and to the armature current as follows

$$T(t) = K_1 \,.\, Ø \,.\, i_a(t) = K_\tau \,.\, i_a(t) \tag{13}$$

By *Laplace* transform:

$$T(s) = K_\tau \, I_a(s). \tag{14}$$

The load torque for motor

$$J\frac{d^2\theta}{dt^2} = T(t) - B\frac{d\theta}{dt} \tag{15}$$

Where,
B is the air friction and bearings friction (Damping coefficient) .

$$T(t) = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} \tag{16}$$

Laplace transformation yields:

$$T(s) = \{J.\, s^2 + B(s)\}.\theta(s) \tag{17}$$

$$G_2(s) = \frac{\theta(s)}{T(s)} = \frac{1}{J.\, s^2 + B(s)} \tag{18}$$

$$\theta(s) = \frac{T(s)}{J.\, s^2 + B(s)} \tag{19}$$

Where Ə is the angle of Rotation:
We can get the motor transfer function:

$$G\,(s) = \frac{\theta(s)}{E_a(s)} \tag{20}$$

$$G\,(s) = \frac{K_\tau . G_1(s) . G_2(s)}{1 + K_\tau . G_1(s) . G_2(s) . H(s)} \tag{21}$$

$$G\,(s) = \frac{K_\tau}{J.L_m.s^3 + (B.L_m + J.R_m).s^2 + (R_m + K_\tau K_m).s} \tag{22}$$

But L_m is small enough so it can be ignored;

$$G(s) = \frac{K_\tau}{J.R_m.s^2 + (R_m + K_\tau . K_m).s} \tag{23}$$

In order to move the two electrodes simultaneously, each with half the required distance, using only one stepper, we need to redesign the whole electrode set which will complicate the design and will deprive the current instruments from utilising the benefit of automatic control. We decided to use two separate stepper motors; one for each electrode, and thus the movement expected of each stepper will be half the required distance. The plastic covering of the mechanism is removed, and each stepper is coupled to the corresponding electrode mechanism through a screw and gear whose transfer ratio (coupling ratio) enables very fine adjustment. This modification can be suggested to the industry to modify the design of the electrodes set to allow for both manual and automatic adjustments.

5. Results and Discussion

The resulting model for computing the number of shocks as a function of patient age (A) and stone diameter (D) is given as:

$$\text{Number of Shocks} = N = 546.667 - 31041 * A + 315.513 * D \quad (24)$$

Now, to obtain the equation that relates the distance to the number of shocks, we gathered data experimentally from Arabic Centre of Lithotripsy (Al-Khalidi Hospital) by measuring the distance between the two electrodes after number of shocks at certain kV. Sources of error include personal, measuring, and random. The following tables and figures show the *Number of Shocks* vs. *Distance* for different values of kV.

Table 6a. Data of electrodes distance and Number of shocks at 16 kV.

Distance (mm)	No. of shocks
0.0	0
0.41	200
0.5	450
0.58	700
0.65	1000
0.69	1500
0.89	2000
0.95	2500
0.97	3000

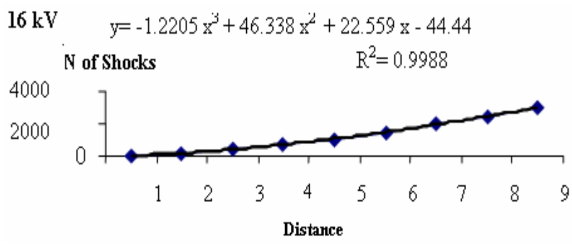
Table 6b. Data of electrodes distance and Number of shocks at 18 kV.

Distance (mm)	No. of shocks
0.0	0
0.05	250
0.17	500
0.49	1000
0.77	1500
0.97	2000
1.17	2500
1.27	3000

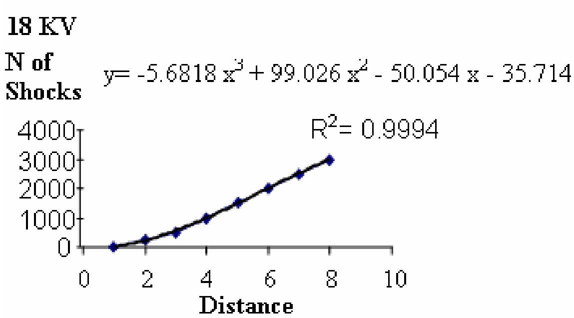
The same behaviour is observed from Figure 6 at different voltage values (kV). Depending on this trend, a fitting curve is obtained for different high voltage values and shown in Figure 7.

Table 6c. Data of electrodes distance and Number of shocks at 20 kV.

Distance (mm)	No. of shocks (shocks)
0.0	0
0.32	250
0.47	700
0.57	1000
0.79	1500
1.17	2000
1.52	2500
1.88	3000



(a)



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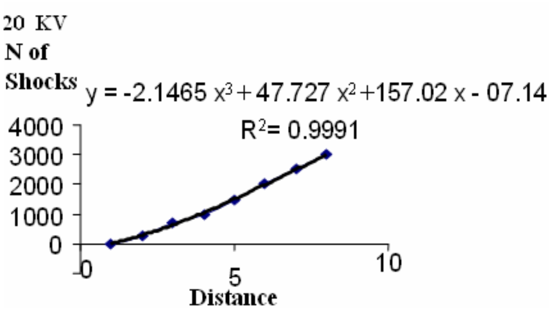

(c)

Figure 6. (a) Shows the relationship between the distance and number of shocks for 16 kV, (b) Shows the relationship between the distance and number of shocks for 18 k, (c) Shows the relationship between the distance and number of shocks for 20 kV

The second half of the model, used in automatic control, presents the relation between number of shocks and distance between electrodes:

$$\text{Distance} = 3.10^{-11}.X^{3} - 2.10^{-7}.X^{2} + 0.0007\ .X + 0.0529 \quad (25)$$

Where *X is the number of shocks.*

Any operator can safely use the software interface of the mathematical model as Equation 24 shows, where patient age and stone size are provided to calculate the suitable number of shocks which is, then, used to find the corresponding distance (ΔD) from Equation 25. The PID controller compares this distance with the safe distance

($\Delta \mathbf{D} \geq \Delta \mathbf{D}_{safe}$) so that when exceeded, it forces the electrodes to return to the reference distance.

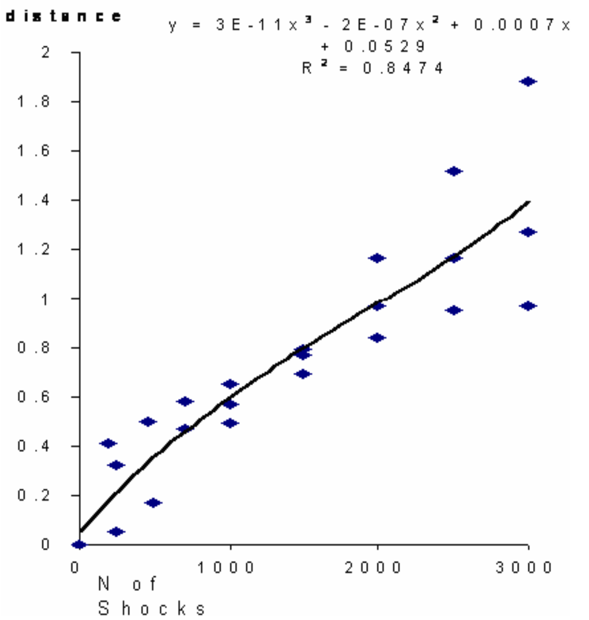

Figure 7. Shows fitting curve relationship between the distance and number of shocks for various kilo Volts.

6. Conclusion

This paper shows that this process has derived a mathematical model that is integrated into a software interface, which allows any operator to treat the patient without the need of highly experienced professionals to determine number of shocks for each case on one hand. On the other hand, and as a consequence, this process will automatically and accurately keep the focal point F_2 in the optimal position which minimizes patient pain and discomfort and saves precious time wasted on calibration conducted by professionals.

The system has been on trials in a number of hospitals and has shown good results. Predictions have, always, been confirmed by professionals and no confliction was reported. The model and control system could be integrated into an expert system, which will enhance performance with time.

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