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DESIGN AND IMPLEMENTATION OF MODEL-BASED CONTROLLERS FOR BIOLOGICAL SYSTEMS

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***Abstract*---Skin cancer is one of the most prevalent cancers worldwide, with millions of cases diagnosed each year. Malignant melanoma, an aggressive form of skin cancer, presents significant challenges in treatment. Early detection and targeted therapies improve survival outcomes. However, conventional drug delivery methods frequently harm healthy cells due to inaccurate dosing. To address these challenges, an electrical analog model of the skin is developed, representing layers such as the dermis, subcutaneous tissues, bones, and muscles. This biological system is formulated into a mathematical model using its electrical circuit equivalent. The objective is to control the drug flow rate to maximize absorption by cancerous cells while reducing diffusion to surrounding healthy tissue. Simulation studies assess drug absorption and diffusion rates across various skin layers. The electrical circuit model is designed using Proteus, while MATLAB analyzes absorption rates for individual and combined layers.**

To enhance control, several advanced control strategies are implemented to regulate drug diffusion rates effectively. A conventional PID (Proportional-Integral-Derivative) controller is integrated to manage the system, and a comparative analysis is conducted between the traditional PID and its optimized version. The optimized PID controller is fine-tuned to minimize error and improve the precision of drug delivery. Furthermore, a Model Predictive Controller (MPC) is also incorporated to predict and adjust the drug delivery dynamically based on future states, optimizing drug absorption and diffusion. A similar comparison is performed between the standard MPC and the optimized MPC, where optimization techniques enhance performance and minimize undesirable diffusion. In addition, an Internal Model Control (IMC) approach is employed to improve the system's robustness and control. The optimized IMC controller is implemented to better handle the dynamics of drug absorption and minimize the effect on healthy tissues. A comparative analysis of PID, optimized PID, MPC, optimized MPC, and IMC controllers provides deeper insights into optimizing drug delivery systems for more effective and controlled skin cancer treatments.

KEYWORDS: Absorption Rate, Diffusion Rate, Drug Delivery, Electrical Analog, Mathematical Modeling, Skin Cancer, Proteus, PID Controller, Optimized PID, Model Predictive Controller (MPC), Optimized MPC, Internal Model Control (IMC), Optimized IMC.

1 INTRODUCTION

A The skin is the largest organ of the human body, serving as a critical barrier that protects against environmental threats, regulates body temperature, and enables sensory perception. It consists of three main layers: the Epidermis, which provides waterproof protection and houses melanocytes responsible for pigmentation the Dermis, containing connective tissue, blood vessels, and nerve endings and the Subcutaneous tissue (hypodermis), which provides insulation and connects the skin to underlying structures.

Maintaining healthy skin is vital, as factors like UV radiation, genetics, and lifestyle can significantly influence its condition. Skin cancer, including Basal Cell Carcinoma (BCC), Squamous Cell Carcinoma (SCC), and Melanoma, poses a major health risk associated with prolonged sun exposure. A thorough understanding of skin anatomy and physiology is essential for developing effective treatment and prevention strategies for various skin conditions.

Skin cancer remains a significant global health concern, characterized by theuncontrolled growth of abnormal skin cells. Among the various types of skin cancer, Basal Cell Carcinoma (BCC) and Squamous Cell Carcinoma (SCC) are the most common. At the same time, Melanoma is known for its aggressive nature and potential for metastasis

Skin cancer, ranks among the most common cancers, with malignant melanoma being particularly challenging due to its aggressive nature. Traditional treatments often cause collateral damage to healthy tissues, highlighting the urgent need for precision in therapeutic approaches. This project pioneers an innovative solution by integrating advanced drug delivery technologies with electrical and mathematical modeling to target cancerous cells while minimizing side effects.

Traditional treatment methods, including surgical excision, radiation therapy, and systemic chemotherapy, have been widely adopted; however, these approaches oftencome with considerable drawbacks, including damage to surrounding healthy tissues and systemic side effects. In response to these challenges, there has been a growing emphasis on advanced drug delivery technologies that aim to enhance the precision of cancer therapies. Controlled drug delivery systems have emerged as a promisingalternative, focusing on targeted delivery of therapeutic agents directly to tumor sites while minimizing systemic exposure.

The integration of smart technology and innovative materials has paved the way for new solutions that allow for real-time monitoring and adjustment of drug release rates. This project specifically explores the integration of these advanced methodologies in the treatment of skin cancer, focusing on the regulation of drug flow rates through the skin

The study employs an electrical analog of the skin, translating biological properties like absorption and diffusion into an equivalent circuit model. Using tools such as Proteus and MATLAB, the system simulates drug dynamics across skin layers, enhancing absorption in malignant cells and reducing diffusion to healthy tissues. To refine control, the project incorporates Proportional-Integral-Derivative (PID), Optimized PID, Model Predictive Controller (MPC), Optimized MPC, Internal Model Control (IMC), Optimized IMC.

offering real-time feedback for optimal drug delivery.

Controlling drug flow rates is critical in skin cancer treatment to ensure effective delivery of therapeutic agents while minimizing side effects. The key parameters that influence drug delivery through the skin include the drug's physicochemical properties, the formulation of the drug delivery system, and the characteristics of the skin itself. By estimating these parameters, it becomes possibleto optimize the drug flow rate and ensure that the therapeutic agent reaches the target site in an effective concentration .To achieve this, the project employs mathematical modeling and simulation techniques to predict the absorption and diffusion rates ofthe drug through the skin layers.

The PID controller plays a crucial role in this process by continuously adjusting the drug delivery rate based on real-time feedback from the system. By integrating advanced algorithms and monitoring systems, the proposed model aims to provide precise control over drug release, facilitating bettermanagement of skin cancer treatment. The significance of this project lies in its potential to revolutionize the approach to skin cancer therapy. By harnessing the advantages of controlled drug delivery systems and integrating smart technology, the proposed method aims to enhance the effectiveness of treatment while minimizing the associated risks. This innovative approach represents a significant advancement in the field of oncology, empowering healthcare providers and patientsto take proactive measures in managing skin cancer.

This research marks a significant advancement in oncology, merging technology with biology to achieve precise, targeted drug delivery. By leveraging control systems and modeling techniques, it opens new avenues for patient-specific therapies, minimizing risks and improving outcomes for skin cancer treatments. The results not only promise enhanced efficacy but also greater safety and comfort for patients.

II LITERATURE REVIEW

Mehta et al. (2021) [1] explored the use of electrical equivalent circuits to model biological systems, focusing particularly on the human cardiovascular system. In their study, the researchers constructed an electrical analog using resistors, capacitors, and inductors to mimic the behavior of blood flow and pressure within the circulatory system. This model enabled real-time monitoring and prediction of physiological responses under various conditions. The study demonstrated that by applying electrical principles to biological processes, one could simulate and controlfunctions such as blood pressure in a similar manner to electrical circuits, providing valuable insights for medical diagnostics and treatments.

Garcia et al. (2022) [2] took a novel approach to model drug diffusion through biological tissues using an electrical equivalent system. Their research represented tissue layers as resistive and capacitive elements, allowing the behavior of drug molecules as they diffuse through the skin to be mimicked by an electrical circuit. This method of modeling has significant implications for transdermal drug delivery systems, as it helps in optimizing drug release rates by understanding how the drug interacts with different tissue layers. By simulating this process through electrical circuits, the study paved the way for more efficient drug delivery techniques, especially in controlled-release systems used for cancer treatments.

Kumar et al. (2023) [3] employed mathematical models to predict the absorption and diffusion rates of drugs through the skin, particularly in the context of skin cancer treatment. Their study involved simulating the dynamics of drug molecules as they penetrate through the various layers of skin, allowing for the optimization of drug delivery rates. The research integrated these models with a Proportional- Integral-Derivative (PID) controller to continuously regulate the flow of drugs based on real-time feedback from sensors monitoring the absorption process. The results showed that such a system could significantly enhance the precision of drug delivery, ensuring that the therapeutic agent reaches its target in the correct dosage while minimizing side effects

Lee et al. (2023) [4] examined the application of Proportional-Integral-Derivative (PID) controllers to regulate drug flow rates in transdermal drug delivery systems. Their research demonstrated how the PID controller could continuously adjust the release rate of therapeutic agents in response to changes in skin absorption rates. This dynamic control is essential for maintaining optimal therapeutic levels, especially in personalized treatments where patient-specific factors can influence drug diffusion. The use of advanced control mechanisms like PID is seen as a majoradvancement in improving the accuracy and effectiveness of drug delivery in cancertherapies.

Smith et al. (2022) [5] explored the effectiveness of transdermal drug delivery systems for treating skin cancer. These systems are designed to deliver drugs directly to the affected skin tissue, providing a more localized treatment that reduces systemic side effects often associated with traditional chemotherapy. The study highlighted the potential of transdermal systems to improve patient outcomes by offering more consistent drug delivery and reducing damage to healthy tissues surrounding the cancerous cells. This research underlines the importance of developing advanced drug delivery mechanisms that focus on targeted treatment for aggressive cancers like melanoma.

Jones et al. (2021) [6] discussed the role of nanotechnology in enhancing the precision of drug delivery systems, particularly in skin cancer treatments. Nanocarriers, which are designed to encapsulate drugs, enable the targeted delivery of therapeutic agents directly to cancer cells. By utilizing environmental triggers such as pH levels or temperature

changes, these nanocarriers can release drugs at the optimal moment, reducing the risk of harming surrounding healthy tissues. The study provided evidence that nanotechnology could revolutionize the way drugs areadministered in cancer treatments, making them more effective and reducing the adverse side effects commonly associated with systemic treatments

Chen and colleagues (2024) [7] highlighted advancements in transdermal systemsdesigned specifically for the treatment of skin cancer. These systems use materials that enhance the permeability of the skin, allowing for the deeper penetration of therapeutic agents. Additionally, the study incorporated real-time monitoring systems that could track the absorption rates of drugs, providing feedback that enables adjustments in the drug delivery process. This integration of technology andbiology has shown great promise in improving the effectiveness of skin cancer treatments, making therapies more patient-friendly by reducing the need for invasive procedures.

III METHODOLOGY

The first phase of the project begins with thorough research to identify the requirements and challenges involved in designing a controlled drug delivery system. Like the physiological monitoring system in the paper, this research focuses on identifying sensors and controllers capable of regulating drug dosage and flow, such as Proportional-Integral-Derivative (PID), Optimized PID, Model Predictive Controller (MPC), Optimized MPC, Internal Model Control (IMC), Optimized IMC controllers for managing drug diffusion rates. A detailed literature review is conducted to analyze existing solutions, particularly those involving drug absorption and diffusion control in biological systems, as demonstrated. This phase also explores factors such as component selection, control algorithms, and power management strategies. The research helps determine the system's overall architecture, including simulation tools like MATLAB for transfer function analysis and Proteus for real-time simulations. Planning involves setting clear project goals, defining technical objectives, and establishing a timeline for completing different stages, much like the detailed drug delivery system.

A. Biological System of the Skin

The biological system of the skin comprises multiple layers, each with unique properties influencing drug diffusion and absorption. These layers include:

• Dermis - The outermost skin layer, which provides the initial barrier to drug diffusion.

• Subcutaneous Tissue - A layer beneath the dermis, composed of connective tissues and fat, which influences the rate and extent of drug absorption.

• Muscle/Bone Layers - Deeper, denser layers that significantly resist drug diffusion due to their structural properties.

Each of these layers presents varying levels of resistance to drug flow and different capacities for drug retention, influencing the drug delivery system's overall performance.

B. Conversion of Biological Model into electrical Model

To accurately simulate and control drug diffusion and absorption through the layers of skin, the biological structure of the skin is trans formed into an equivalent electrical circuit model. This model facilitates precise control of the drug delivery process by allowing each skin layer to be represented by fundamental electrical components. This approach makes it possible to simulate the drug's behavior as it encounters different types of tissues, allowing the system to manage drug flow and absorption rates effectively

Resistance (R): Represents the ability of each skin layer to impede drug diffusion. Denser layers like muscle and bone offer higher resistance, while the dermis and subcutaneous tissues exhibit moderate resistance.

Capacitance (C): Simulates the ability of a layer to retain drugs temporarily. For instance:

- The dermis has moderate capacitance due to its permeability.
- Subcutaneous tissue, rich in connective tissue and fat, exhibits higher capacitance.
- Muscle and bone layers have lower capacitance due to their compact structure.

Electrical System Configuration : The layers are arranged in series and parallel configurations based on their biological characteristics. This setup enables a precise representation of drug flow resistance and retention dynamics through the skin .This electrical modeling approach provides a robust framework for simulating drug diffusion and absorption.

C. Functional Overview of the Electrical Model

The electrical model effectively simulates drug movement across the skin layers by combining resistors and capacitors to represent each layer's distinct physical properties. This approach enables real-time adjustments to drug flow based on the observed behavior in simulations:

• Controller Integration By monitoring drug diffusion through the equivalent electrical circuit, the controller dynamically adjusts drug flow to ensure that therapeutic levels are achieved in cancerous cells while minimizing diffusion to surrounding healthy tissues.

• Real-Time Behavior Simulation This model supports precise control over drug delivery, as the controller can modify the flow rate based on the impedance each layer presents. For example, if a layer's resistance or capacitance indicates slower diffusion, the controller can adjust dosage rates to ensure consistent drug absorption in the target tissue.

The equivalent electrical circuit model provides a reliable foundation for optimizing targeted drug delivery, ensuring that the drug concentration is focused where it is most needed and minimizing side effects on healthy cells. This model also allows for accurate predictions of how the drug will behave across various tissue structures, supporting safe and effective treatment delivery.

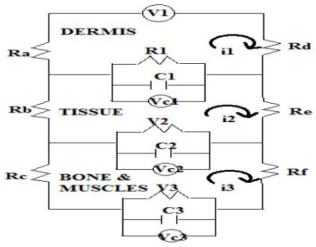


Figure 1 Equivalent Electrical System

D. MATHEMATICAL MODELING

The mathematical model of the drug delivery system is based on Ohm's Law and Kirchhoff's Circuit Laws, which provide the framework for converting biological diffusion and absorption properties into an equivalent electrical circuit model. This model enables precise control and prediction of drug concentration and flow through each skin layer. The key steps involved in mathematical modeling.

Applying Ohm's Law and Kirchhoff's Laws:

Ohm's Law - Defines the relationship between the applied drug concentration (analogous to voltage) and drug flow (analogous to current) through each layer.

Kirchhoff's Circuit Laws - Used to analyze how drug flow divides and interacts across layers, accounting for series and parallel configurations to accurately model drug movement through each layer.

E. TRANSFER FUNCTION

Each skin layer is represented by a unique transfer function, describing its response to a drug input.

1. Dermis Layer:

$$\frac{V_{c1}(s)}{V_1(s)} = \frac{s + 2.857}{s + 0.909}$$

2. Dermis + Tissue Layer:

$$\frac{V_{c2}(s)}{V_1(s)} = \frac{s^2 + 2.857s + 2}{s^2 + 3.766s + 2.597}$$

3. Dermis + Tissue + Muscle Layer:

$$\frac{V_{c3}(s)}{V_1(s)} = \frac{s^3 + 4.857s^2 + 9.047s + 19.048}{s^3 + 5.766s^2 + 4.597s + 5.195}$$

Models the cumulative response of the dermis, tissue, and muscle/bone layers, providing an overview of how the entire system responds to drug input.

F. ELECTRICAL PARAMETERS

Resistance Values : Each skin layer has a unique resistance value, reflecting its biological density and permeability to drug flow. These values simulate the physical barrier that each layer poses to drug diffusion. The resistance values used in this model are as follows :

RESISTANCE	VALUES (OHM)
R_a	0.09
R_b	0.09
R_c	0.5
R_d	0.5
R_e	0.8
R_f	0.8
R_1	0.5
R_2	0.8
R_3	0.6

Table 1 - Resistance Of The Skin

Capacitance Values The capacitance of each layer represents its drug storage capacity, simulating the temporary retention of the drug within each layer before diffusion to the next layer occurs. Capacitance values for each layer are as follows:

CAPACITANCE	VALUES (FARAD)
C_1	0.4
C_2	0.4
C_3	0.4

Table 2 – Capacitance Of The Skin

The resistance and capacitance values together allow for an accurate simulation of drug behavior as it moves through each layer, helping achieve controlled and targeted drug delivery.

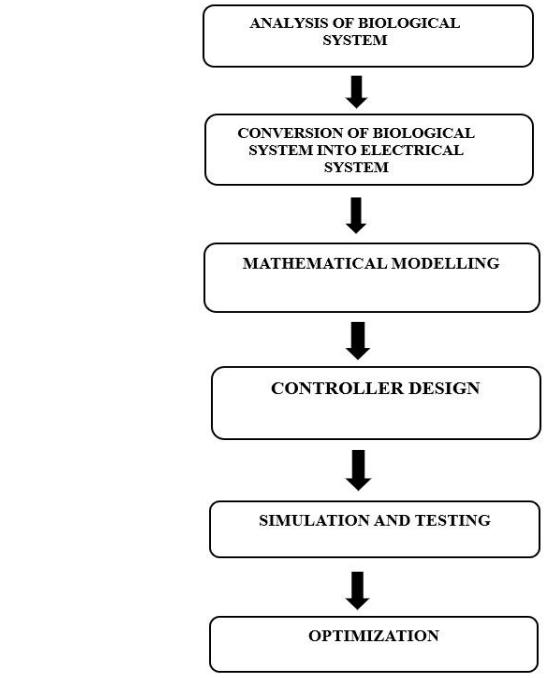


Figure 2- Flow chart

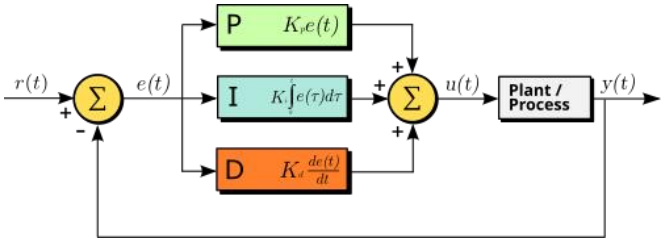


Figure 3-Block diagram of PID controller

IV.SIMULATION RESULT AND ANALYSIS

The simulation examines how each layer of skin absorbs and diffuses the drug at different input concentrations, simulated using varying voltage levels. The outputs are analyzed for both 5V and 10V inputs to observe changes in absorption and diffusion behavior.

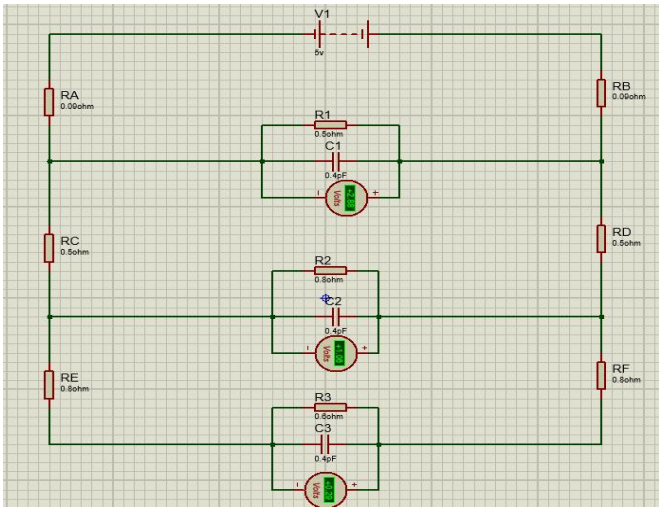


Fig 4-Simulation Result for 5V

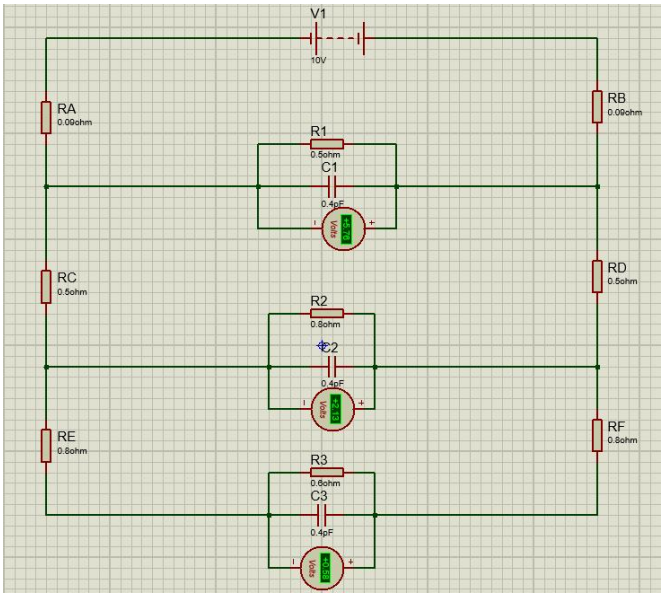


Fig 5-Simulation Result for 10V

The following tables 3 and 4 shows the absorption and diffusion rate of the drug by each compartment at different sample inlet voltage(drug) respectively.

ABSORPTION OF THE LAYERS	OUTPUT VOLTAGE(V)
Inlet Drug	5
Dermis	2.88
Dermis & Tissue	1.06
Muscles &Bones	0.29
Total Absorption	4.23
Diffusion	0.77

Table 3-Output Comparision for 5V

From the Table 3 it is inferred that when 5V (assumed to be the drug) is given as input to the network, the amount of drug diffused from the system is found to be 0.77V and the total absorption rate by all the three layers is 4.23V.

The diffusion rate of drug is given by the equation below,

Diffusion = Inlet Drug – Total Absorption

ABSORPTION OF THE LAYERS	OUTPUT VOLTAGE(V)
Inlet Drug	10
Dermis	5.76
Dermis & Tissue	2.13
Muscles &Bones	0.58
Total Absorption	8.47
Diffusion	1.53

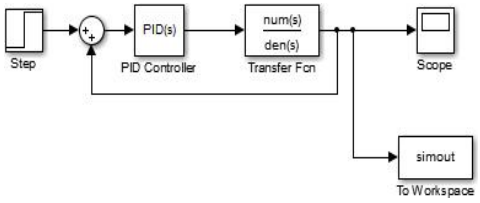
Table 4-Output Comparision for 10V

From the Table 4 it is inferred that when 10V (assumed to be the drug) is given as input to the network, the amount of drug diffused from the system is found to be 1.53V and the total absorption rate by all the three layers is 8.47V.

The response plot for each layer like dermis, tissue and the total compartment (Dermis ,Tissue, Bone and Muscles) indicates the amount of drug absorbed by each layer. The absorption capacity of each layer is obtained by calculating the area under each curve.

Area = 1/3(bh+ lb)

Where, b is breadth of the triangle considered, h is height of the triangle considered from the plot, l is length of the rectangle considered, b is breadth of the rectangle considered from the plot



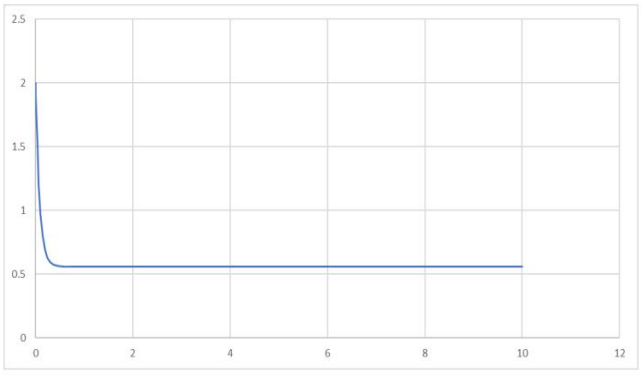


Figure 6 Response of the Dermis Layer

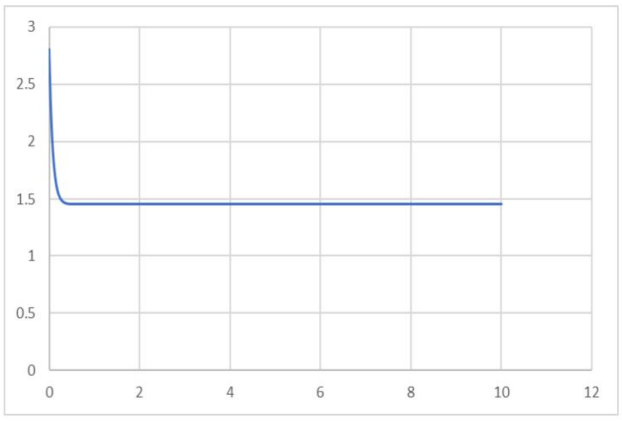


Figure 7 Response of the Dermis and Tissue Layer

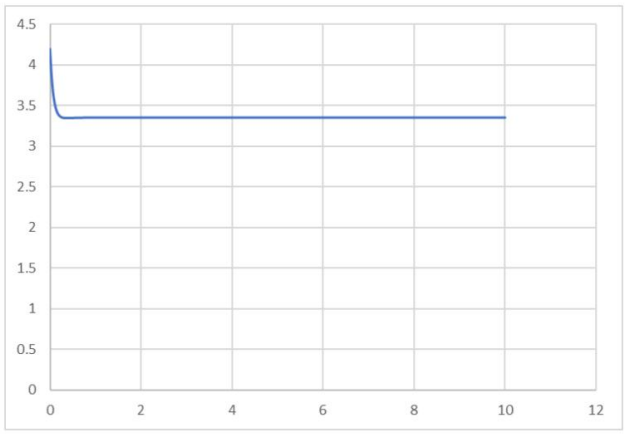


Figure 8 Reponse of Three Layers

SIMULINK MODEL FOR DRUG DELIVERY SYSTEM WITH CONTROLLER

Figure 9 SIMULINK Model for Drug Delivery System with Controller

V. RESULT AND DISCUSSION

The controller-based automatic drug delivery system developed in this study aims to achieve precise, targeted drug delivery. By modelling biological properties as equivalent electrical components, this system enables controlled management of drug absorption and diffusion across various biological layers. The primary objectives were to optimize treatment effectiveness, maximize drug uptake in targeted areas, and minimize side effects through accurate flow rate control.

The flow rate control mechanism in this system is designed to regulate drug absorption specifically within layered biological tissues, such as the dermis, tissue, and muscle-bone compartments. Each layer's unique resistance and capacitance properties are modelled electrically to simulate how drug flow interacts within each compartment, allowing for precise absorption control.By adjusting the input flow rate, the system

can control how much drug each layer absorbs, ensuring higher initial absorption in the outermost layers (e.g., dermis) while gradually decreasing as the drug penetrates deeper. This targeted control is particularly beneficial for treatments requiring localized dosing, as it limits drug spread to surrounding healthy tissues.The system's capacity to finely modulate flow rates allows for patient-specific adaptations, which can enhance therapeutic effectiveness in treatments like cancer therapy. This precision ensures that the drug reaches only the affected areas, minimizing side effects while maximizing treatment efficiency.

Compared to traditional drug administration methods, this controller-based system offers significantly improved precision by managing flow rates and minimizing diffusion. Unlike conventional methods that lack compartment-specific targeting, this approach enables targeted drug delivery and aligns with best practices in modern medical technology, providing a safer, more effective option for treatment

V.CONCLUSION

This project addresses a critical need for precision in skin cancer treatment by developing a controller-based drug delivery system. The system uses an electrical analog model of skin layers and incorporates advanced control techniques such as Proportional-Integral-Derivative (PID), Optimized PID, Model Predictive Controller (MPC), Optimized MPC, Internal Model Control (IMC), Optimized IMC to regulate drug flow rates. Simulation results demonstrate the system's potential to improve targeted drug absorption while minimizing drug diffusion to healthy tissues. By enhancing therapeutic outcomes and reducing side effects, the proposed approach ensures greater patient safety and effectiveness in treatment. Despite challenges related to biological variability and the lack of real-time feedback, the system lays a strong foundation for future advancements in controlled drug delivery

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