Simulation of Transdermal Toxin Expulsion via an Adsorptive Dermal Patch

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Introduction

Human skin is a highly complex organ made of multiple composite layers, including the subcutaneous tissue, the dermis, and the epidermis. These layers contain ducts and pores that allow substances to pass into or out of the body[1]. Topical application of activated charcoal (AC) poultices and packs stimulates circulation, causes sweating that excretes toxins, and draws out impurities. Although it is clinically proven that these noninvasive treatments can help to rid the body of many different toxins and infections, it is generally reflected that such method lacks scientific explanation. Activated charcoal possesses an extraordinarily large surface area and pore volume, making it suitable for a wide range of applications, including toxin removal[2,3]. In this work, we focused on topical application of charcoal poultices or commercial dermal patches, specifically in understanding the transdermal toxin expulsion mechanisms through a simple 2-D model (according to the diagram shown in Figure 1) in COMSOL Multiphysics®.

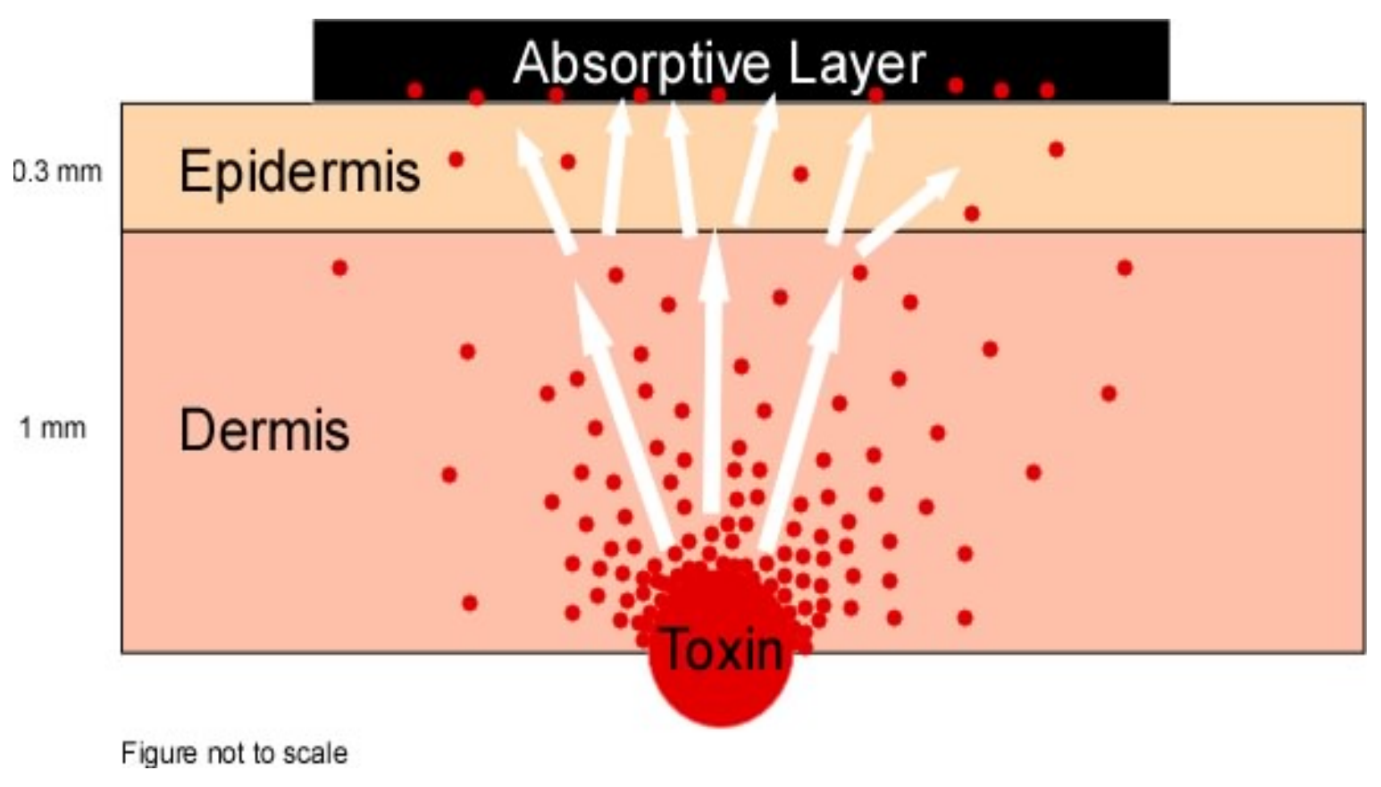

Figure 1: Diagram of a 2-D model with a point-source toxin diffusing into a thin absorptive layer.

Computational Methods

We developed a 2-dimensional multilayered skin model that consists of the epidermis, dermis, and hypodermis with a topical adsorptive layer (AC). The skin is modeled as a homogeneous slab with surface area that is larger than the thickness. The therapeutic patch was approximated by using an infinitely thin boundary. The governing equations are as follows:

Mass transport by diffusion using the Fick's equation

$$\frac{\partial c}{\partial t} = D\nabla^2 c$$

Adsorption using Langmuir adsorption theory

$$c + s \underset{k_{des}}{\overset{k_{ads}}{\rightleftarrows}} c \cdot s$$

$$-\frac{\mathrm{d}c}{\mathrm{d}t} = k_{ads}[c][s]_0(1-\theta) - k_{des}\theta \qquad \text{where} \qquad \theta = \frac{[cs]}{[s]_0}$$

The boundary condition couples the reaction for the substance c

$$\mathbf{n}\cdot(-D\nabla c) = k_{ads}c \cdot s_0(1-\theta) - k_{des}cs$$

PDE with weak-form solution for boundary surface reaction [4]

$$0 = \int_{\Omega} v\left(k_{ads}c - k_{des}cs - \frac{\partial cs}{\partial t}\right)\mathrm{d}A$$

Using the test function: $test(cs)\cdot(k_{ads}\cdot c - k_{des}\cdot cs - cs_t)$

The geometry was turned into a non-equidistant mesh, smaller at the surface where the charcoal would absorb the toxin. We ran tests with short and long source toxin exposure times to determine how different carbon levels in patches would react to toxin changes, and we theoretically measured what percentage of toxin removal a certain level of AC carbon dose in a patch would contribute.

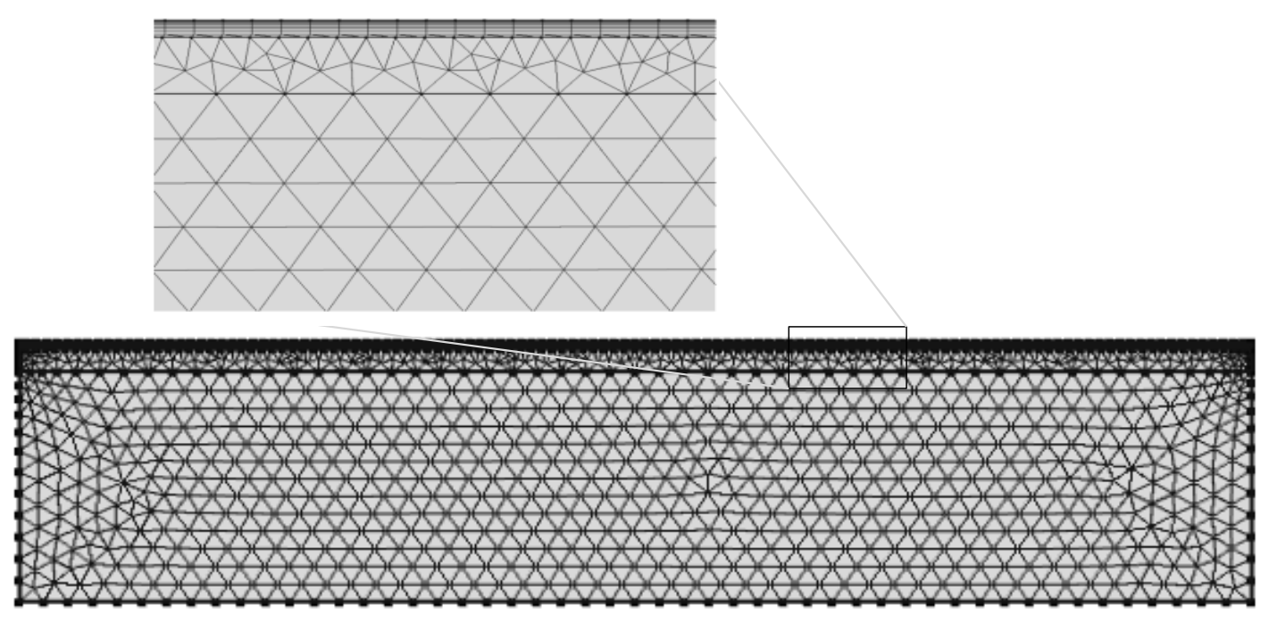

Figure 2: Non-equidistant mesh, concentrated at surface of absorption

Results

Depletion Boundary Layer

The reaction was found to be diffusion-limited, as the Damkholer number revealed and as seen in the figure below.

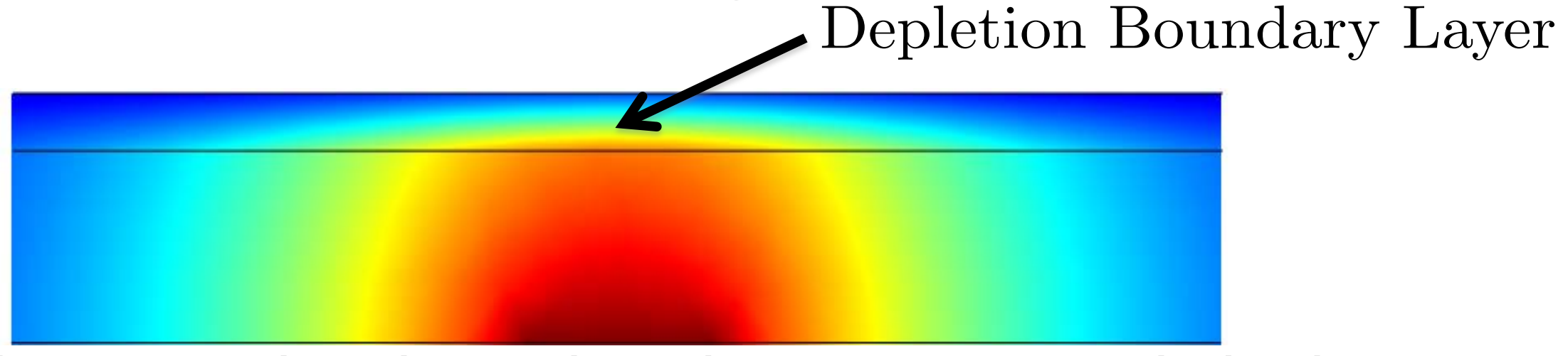

Figure 2: The simulation shows transport-limited diffusion near adsorptive surface.

Kinetics of Adsorption

During a short-term exposure, for 90% removal, the patch reduced the removal time by over 70% for highly reactive AC. For long-term exposure, the concentration levels off toward an asymptote with a patch.

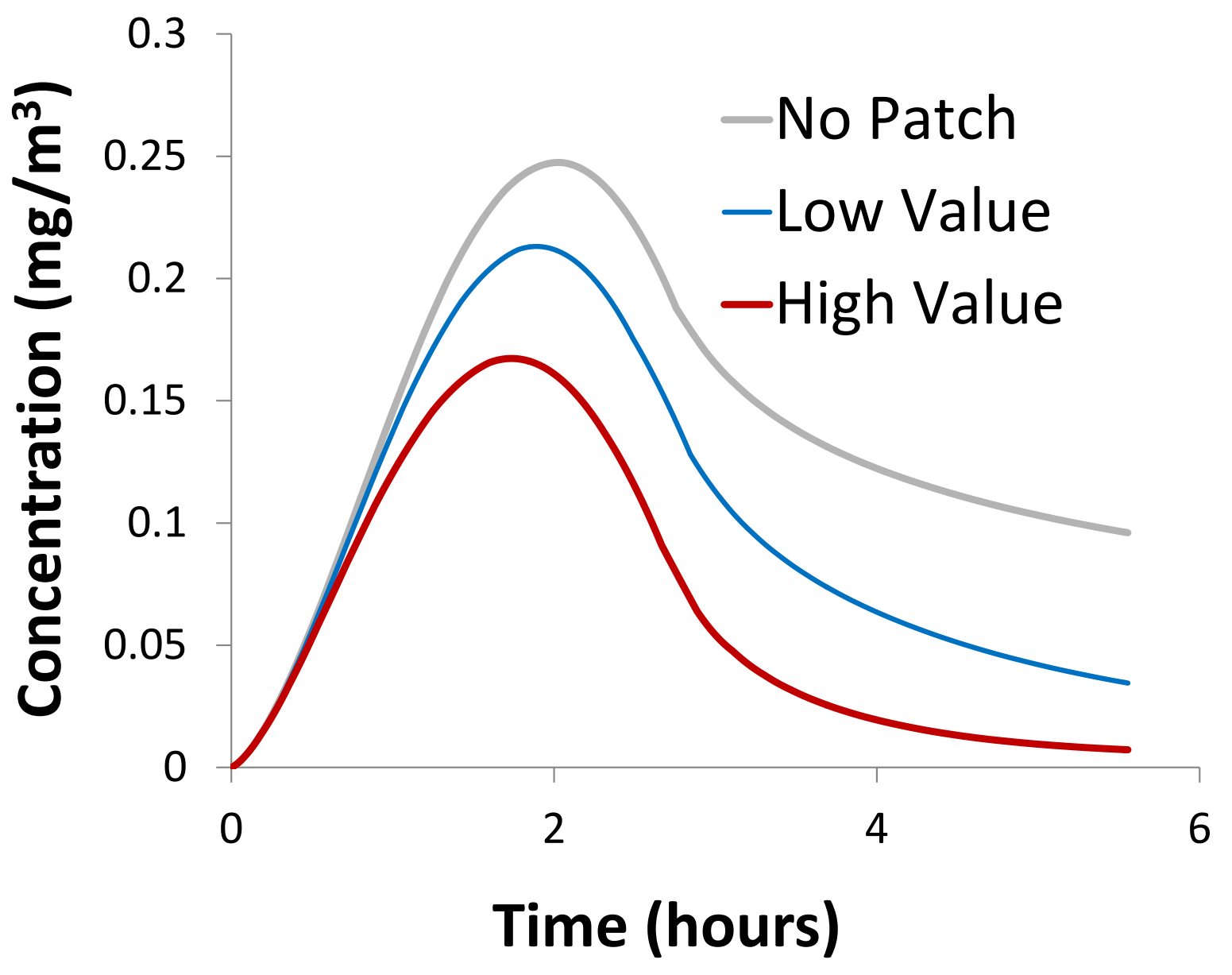

Figure 3: Concentration dissipation for several carbon doses in short-term toxin exposure tests for no patch, low reaction rate, and high reaction rate constants.

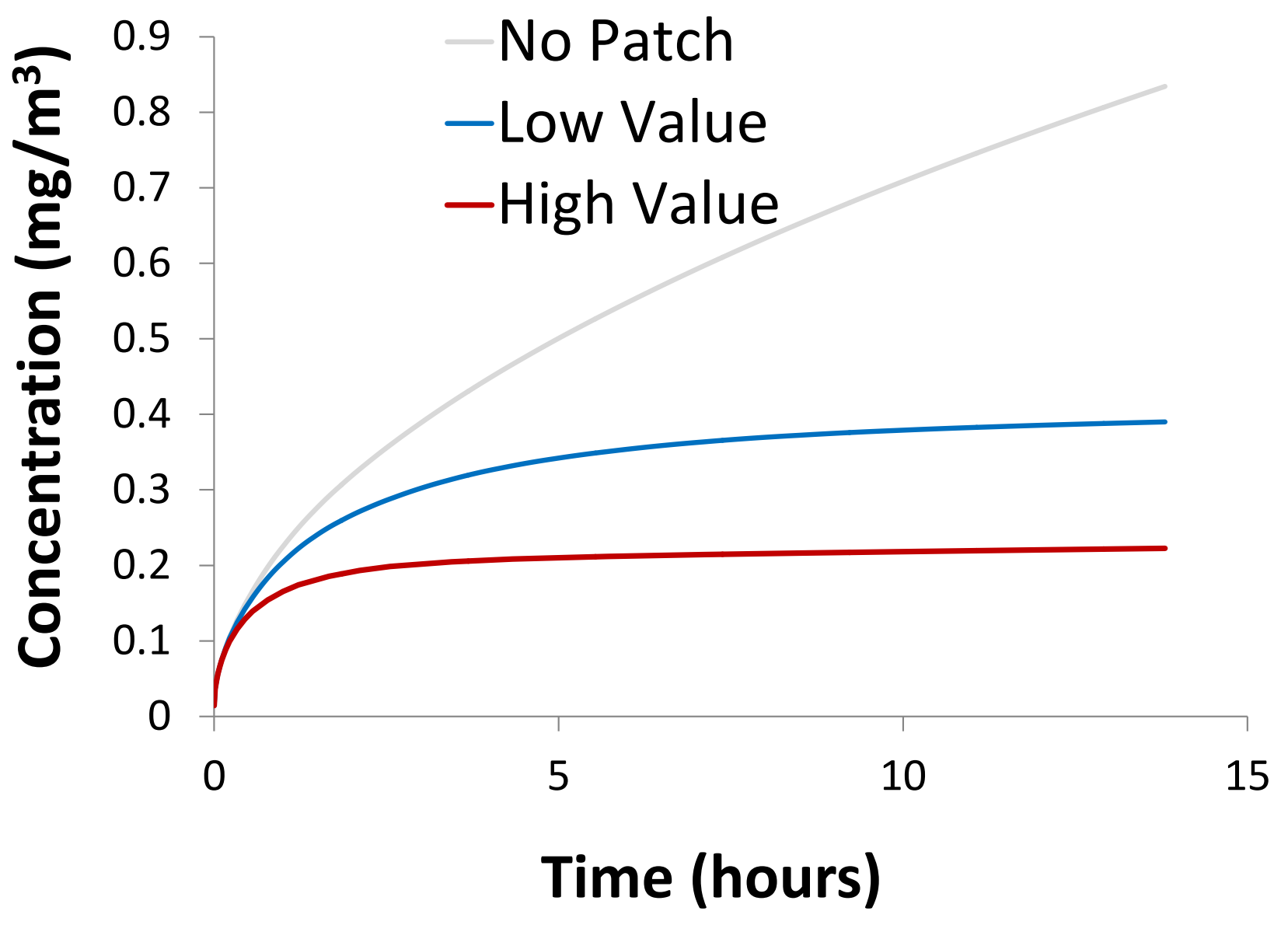

Figure 4: Concentration graphs for several carbon doses in long-term toxin exposure tests for no patch, low and high reaction rate constants

Effect of Activated Charcoal Composition

Commercial activated patch composition varies greatly depending on the product. Figure 5 show that at 10% of composition, the removal rate is approximately 60% of its maximum capacity.

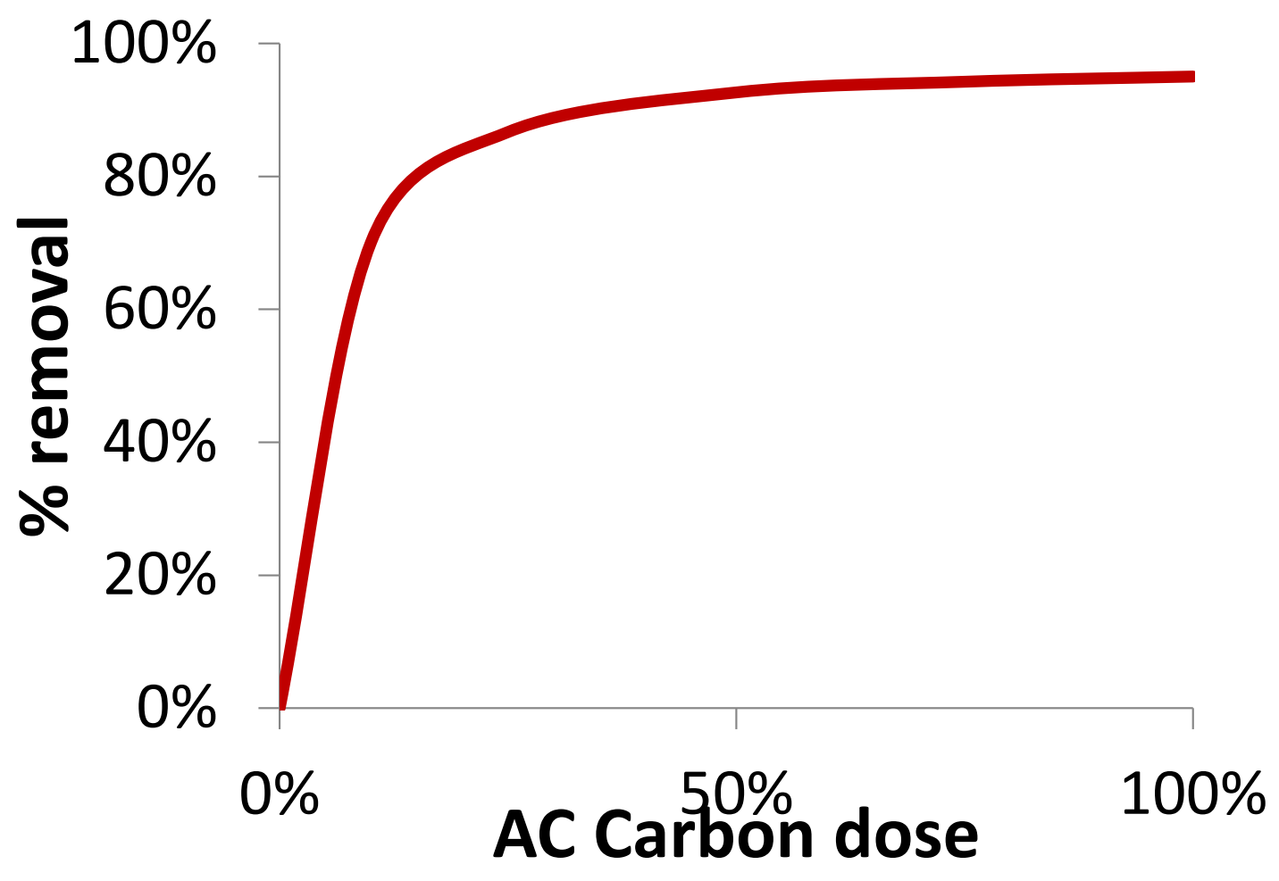

Figure 5: Percent removal of toxin with percentages of carbon doses

Conclusions

This study represents what is to our knowledge the first attempt to create a mathematical model to account transdermal delivery of an internal substance out to the skin with the aid of a topical application of adsorptive layers to draw out impurities. For many years, we have known of the efficacy of dermal application of activated charcoal only clinically, but a scientific model or explanation has been lacking. This COMSOL model allows both a large degree of flexibility in shaping geometry and easy interpretation of the computations, so this work can be expanded to study different geometry and structures of skin models for higher utility. Although several assumptions were used to make the otherwise complex model simple, the model successfully showed how the concentration of a toxin in the skin can be reduced significantly faster with an external, topical adsorptive patch.

References

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