# Needle Deflection

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February 13, 2019

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## 1 Abstract

Radiofrequency ablation (RFA) treatments are delivered to small-to-medium inoperable tumors using high temperature obtained electrodes (needles). One or more needles are inserted into the target and will be susceptible to deflection due to insertion errors and patient movement. This paper utilizes the two-stage RFA inverse planning problem. The paper addresses the need of adjustment of parameters in treatment plans under needle deflection. Quantitative results of needles deflected radially along the correct orientation or under different orientations are presented. The relationships between the deflection distance

and tumor under-dosage and organ-at-risk (OAR) over-dosage are illustrated to demonstrate the effects of needle deflection.

# 2 Introduction

Radiofrequency ablation (RFA) uses focal ablation to treat small-to-medium sized inoperable tumors by inserting electrodes (needles) percutaneously or via open surgery into the tumor, and high frequency alternating current is passed through the needle, generating heat to ablate the target. RFA has the potential for incomplete ablation when the needle is incorrectly placed and when heat passing through the needles is insufficient.

In the two-stage method in Inverse planning for RFA using multiple damage models [1], a volume of ablation has been approximated to an ellipse or a sphere which covers the target tumor entirely, and needle position and orientation has been computed for single needle or multiple independent single needle scenarios, where clustered needles with relative fixed positions are treated as a single needle. This result is then used to find, for a fixed treatment time, the minimum initial voltage required to pass through the needles that enables full target coverage. However, problem arises when the inserted needles tend to bend depending on various parameters: Tip assymmetry, stiffness of needle and tissue, tissue anistropy, respiratory and other factors all deviate the needles from its intended path and the degree of deflection are hardly predictable due to the complex combination of parameters [2, 3]. Any misplacement in the needle orientation or position of needle insertion could easily jeopardize the targeted damage because the volume of ablation do not match the calculated volume of coverage. Therefore, the main motivation of our analysis is the performance of tumor ablation under needle deflection. We also hope to see how the damage to organ-at-risk (OAR) will be affected by needle deflection and whether there are better insertion locations that allows for full target coverage and has less damage to the surrounding OAR than the calculated needle position.

# 3 Background

Current techniques on assisting needle insertion and tracking needle positions in RFA include computed tomography (CT)-guided, magnetic resonance (MR)-guided, fluoroscopy-guided and ultrasound (US)-guided procedures [3]. However, these modalities have their limitations, for example, inadequate visibility of the target, high per case setup time and other individual limitations for each technique [3]. Complete ablation often cannot be achieved in one treatment session even with the assistance of image guidance techniques, for example, local recurrence rate after US-guided RFA ranged from 1.4 to 41% [4]. Thus it is crucial to analyze the impact of needle deflection on ablation and take into account the possibilities of underdosage in treatment properly.

Existing work to account for inaccuracies in needle placements in RFA include finite-element simulation on liver tumors [5], which uses liver and tumor perfusion rates as well as the tumor geometry as input parameters and simulate the ablation process using the model presented by Kroger et al [6]. Their findings entail that imperfect positioning of needle can result in undertreatment of the tumor especially when the needle is positioned offset to the tumor center. Another model proposes a needle-tissue interaction model to predicts needle deflection, where its adaptive slope model combines offline needle bending predictions with online needle bending predictions and adaptive corrections, using needle-tissue properties, needle tip asymmetry and updates of needle tip position [2]. Research has not been done that investigates how much the parameters to a treatment plan needs to be adjusted when the needle is deflected to a certain amount, hence motivating us to perform simulation on this matter.

# 4 Methodology

The procedure to evaluate the effect of needle deflection follows the implementation of the two stage RFA inverse planning problem [1]. The first stage, needle orientation optimization (NOO), approximates the needle position and orientation. The second stage, thermal dose optimization (TDO), utilizes the outputs from the first stage in order to compute the thermal dosage received by the tumor and OAR.

We divide the target tumor and the organs-at-risks (OARs) into unit grids called voxels ("volume pixels"). In NOO, we approximate the ablated region to an an ellipse or sphere that covers the entire tumor. Boundary voxels of the target tumor are first found using the grassfire algorithm [7] for time efficiency. We then fit a minimum volume covering ellipse (MVCE), or minimum volume covering sphere (MVCS) using the boundary voxels of the tumor. An optimized center location of the ellipse or sphere and orientation of the inserted needle can then be found using singular value decomposition on the output of MVCE or MVCS.

Using the optimized center of ellipse, we use needles of a fixed length and find initial voltage of the needle using thermal dose optimization. The tip length of the needle is found Thermal dose optimization uses Pennes' Bioheat Transfer Equation (BHTE) [8] and Arrhenius thermal damage model (ATDM) [9–12], which are two conventional models. BHTE computes the temperature at each given time step using the following equation:

$$\rho_t c_t \frac{\partial T}{\partial t} = K\Big(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\Big) - c_b \rho_b w (T - T_a) + Q_m + Q_p \tag{BHTE}$$

However, BHTE does not consider the length of time each voxel is exposed to a temperature. ATDM is an alternate damage model which uses a voxel's temperature history, the result from BHTE, to determine tissue damage. ATDM computes the thermal damage using the following equation:

$$\Omega_{js}(t) = \int_0^t A \exp\Big(\frac{-E_A}{RT(t)}\Big) dt \tag{ATDM}$$

## 4.1 Translation

In order to identify the new needle positions due to needle deflection, we establish a sphere of radius 2mm centering the optimized center of ellipse and all voxels in the sphere. We treat each voxel in the sphere as a possible center of needle due to needle deflection.

There are three parameters taken into consideration in inverse planning: input voltage, needle size, and treatment time. For simplicity, we set the needle size and treatment time as 10mm and 15 minutes, respectively. Using the algorithms, the minimum voltage required to cover a given tumor is found. Each plan is evaluated using two different models. For the BHTE temperature model, any molecule is considered damaged if the tumor or OAR reaches 60 degrees Celsius (or 333 degrees Kelvin) at any given time. For the ATDM, a molecule will receive irreparable damage if its damage index reaches 0.63. The minimal voltage applied at the tumor center, where the whole tumor is considered killed for one or both models, is denoted as minimum voltage, or V0. The amount of OAR being killed is recorded.

The accuracy of the needle placement is defined as the deviation (in mm) from the center of the optimized ablation volume. It is simulated that the needle being inserted can be deflected, in any direction, by as much as 2mm from the planned location due to reasons such as insertion errors, respiratory or patient movement. To decide for the possible deflected locations, every voxel in the target structure is checked to see if its Cartesian distance from the center computed above is less than 2mm in the 3D space using the Euclidean distance equation:

$$d(c,q) = \sqrt{\Big((c_1 - q_1)^2 + (c_2 - q_2)^2 + (c_3 - q_3)^2\Big)} \tag{1}$$

where c is the center and q is the new center due to deflection. Both positions are in three-dimensional Euclidean space.

Due to internal deflection, needles can be at different positions with different orientations. To determine the effects of deflection, each plan is recomputed with every possible needle position/orientation. Then the data is analyzed mainly to address two ideas: the likelihood of change of plan to take into account and the necessity of change of plan. The change in OAR damage due to deflected needle is also recorded.

## 4.2 Single Needle Deflection

There are three different liver tumor cases being used for this experiments, which are given case numbers 1 to 3. Each individual tumor is also added with three different sizes of margin, and are denoted as 'S', 'M', and 'L' to represent small, medium and large margin, while 'N' is used to represent 'No Margin'. Thus there are four cases different cases for each tumor case, denoted as '1N', '1S', '1M', and '1L', and in total of 12 cases across the three tumor cases used for experimenting. The optimal input voltage and needle size have been found based on previous experiments by other scholars, and are used as a base case for treatment plans with deflection. Within the 12 cases, all four cases of the first tumor, as well as the second tumor with no margin added, have been recommended to use only a single needle for ablation for the base case; while all the other cases are recommended to use multiple needles. For this experiment, it was decided to use needle size and number of needle consistent of what was recommended for the base cases, and increase the voltage by increments of 2.5 volts until the tumor is fully covered for all deflected cases.

## 4.3 Multiple Needle Deflection

For cases where it is recommended to use multiple needles, the needle deflections are setup a bit differently. If there are two needles required for a particular case, and the same setup from single needle was used, namely a 2mm sphere are constructed for each of the two needle center, and all voxels within the spheres are treated as possible deflected center, then there would be n * m of possible combinations of locations for the two needles, where n is the number of deflected centers for first needle and m is for the second needle. To evaluate all the plans with every possible needle deflection, n * m trials would be performed. In summary there is an exponential increase in number of trials performed when the number of needles for a tumor is increases, this would cause issue in allocation of both computational power and time. As a result, we would need another approach for multiple needles, instead of treating each of the multiple needles as single needles.

As an alternative, it is purposed to assume the Cartesian distance of the needle center deflected from the base case center to follow Gaussian distribution, with the mean value of distance deflected to be zeroand standard deviation arbitrarily set to be 1mm. Then the possibility of the needle deflected to each center is accessed. It is then discovered that, based on the distribution there is a 80 percent chance of the needle to deflect 1.28 mm or less. As a result, a 1.28 mm radius sphere is constructed for each needle for the multiple needle case, and all combinations of voxels within the new spheres across each needle would be considered a possible needle center combination. By shrinking the size of the sphere to 1.28 mm, the computational power required has been effectively reduced by 95 percent, while we are still able to gain insight on needle deflection, since the trials elinimated have a low chance of happening, based on the distribution.

## 4.4 Deflection

The second part of the project focus on the effect of change of needle orientation to the quality of the treatment plan. Moreover, in practice it is found that the needle inserted can have vertical orientation deflection easily, meaning the needle has a high chance of tilting upward and downward. Thus after the initial orientation of the needle is found using the optimization algorithm and denoted as the base case orientation, the direction vector representing the needle's orientation is changed by altering its value on the z-axis, while keeping the x and y values unchanged. This way the new direction vectors will point directly upward and downward from the base case, to simulate the needle tilting upward and downward in real life scenarios. The new orientations represented by the new direction vectors will be used in the BHTE and ADTM models to evaluate treatment plans quality with deflected orientation.

# 5 Results

## 5.1 Undeflected Case

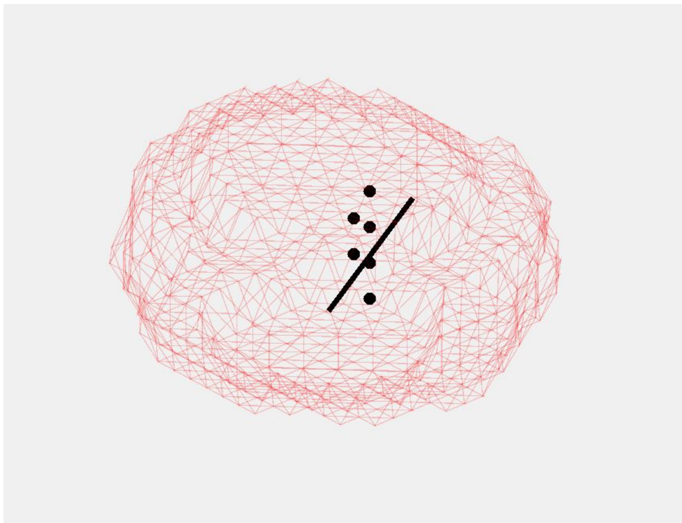
For the case 1 tumor, the optimal needle center location is found to be (35.2360, 34.3869, 47.1459) in Cartesian coordinates, with its orientation represented by the direction vector (-0.8660, -0.4994, 0.0256). It is found that a minimum voltage of 20 is needed for the tumor to be sufficiently ablated. The amount of damage required for a tumor to be entirely damaged is for every tumor voxel to receive at least 63% damage from the ATDM model and to achieve at least 60 degrees in Celsius in the BHTE model. With this input voltage, there is 0.8 percent and 1.5 percent of the rest of the target structure (which is treated as OAR) being overdosed according to ATDM and BHTE, respectively.

## 5.2 Translation

In this section, we simulate that the needle is deflected under the optimized orientation but is inserted at a position close to the optimized center location. From the 2mm sphere centered at the optimized needle center, 35 voxels has been identified and each location is a possible deflected center. We tested for both the 10mm and 7mm needle. When the initial voltage is 20 for the 10mm needle, the tumor suffers from 1.22% to 10.02% of under-dosage for all 35 possible deflected centers, as shown in Figure 1. On the other hand, according to the BHTE model, 34 out of the total 35 possible deflected centers would result in the tumor being sufficiently covered. Of the position that is under-dosed, only 1 voxel in all 889 voxels of the tumor is under-dosed. If it is assumed that all deflected centers are equally likely to occur, than this makes 97 percent chance for the original plan to be accepted, despite deflection.

When we increase the initial voltage to 21, BHTE suggests that all tumors voxels are ablated. However, none of the 35 deflected centers receive sufficient damage according to the ATDM model, even though the amount of under-dosage does decrease to a range of 0.022% to 6.57%. Interestingly, the output from the ATDM model suggests that several deflected positions receive greater than 99% damage and have less OAR damage than the original optimized center. These positions could potentially be better than the original plan and are shown in figure 5.2. As the voltage increases from 21V to 25V, the number of potentially better positions also increase.

One interesting result in the analysis of the damage to the OAR is that when the needle is inserted correctly, the OAR damage is higher than when the



needle is deflected. In the ATDM model, when the initial voltage is 20, 0.79% of OAR has been damaged when the needle is correctly inserted. However, under deflection, the OAR damage ranges from 0.52% to 0.55%. Increasing the voltages to 21V and 26V also show the same trend.

Assuming the voltage input can only be whole numbers, the minimum voltage needed for ablation of tumor for the BHTE model and the ATDM model are found to be 21V and 26V, respectively. Even though 21V appears to be sufficient voltage according to BHTE model (Figure 1), the tumor is still lacking damage according to ATDM (Figure 2), for every single possible deflected center. However, the amount of under-dosage does decrease from 10.02% to 6.57% percent for the worse case scenario from 20V to 21V. It is only when the initial voltage is increased to 26V that all tumor voxels receive sufficient damage in the ATDM model. The drastic difference in the results from the two models, ATDM and BHTE, suggest that ATDM could be more informative and reliable in predicting whether the tumor receives sufficient damage.

When the length of needle is set to be 7mm and using the ATDM model, the initial voltage needs to be at least 26V to ablate the tumor when the needle is positioned correctly. However, at a voltage of 25V, even though 0.22% of the voxels in the base case are not sufficiently ablated, there are 8 out of 35 deflected positions that do ablate the tumor entirely. The positions of these deflected tumor centers are shown in figure 3. All these deflected positions do cost more damage to the OAR compared to the original center (0.79% - 0.82% compared to 0.65%) (see figure 4), but considering the regenerating properties of a liver, we still consider these 8 positions to be better plans than the calculated position of needle insertion, at a voltage of 25V. On the other hand, the BHTE model suggests that the original position as well as all 35 deflected positions will ablate the tumor entirely.

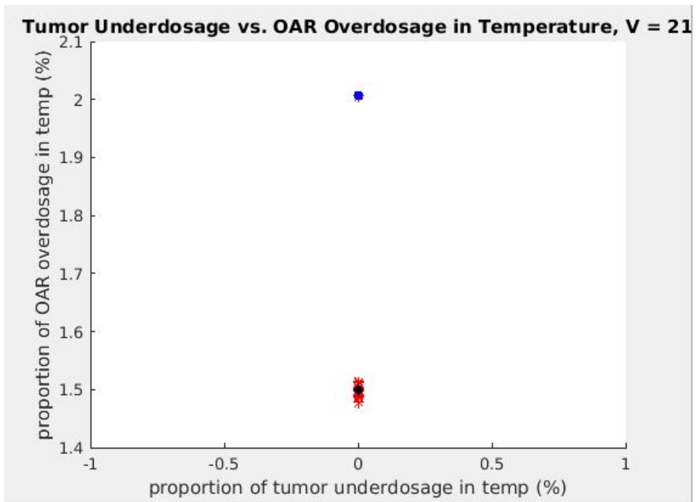



Figure 1: BHTE Tumor Underdosage vs OAR Overdosage, with lambda = 10mm and V = 21

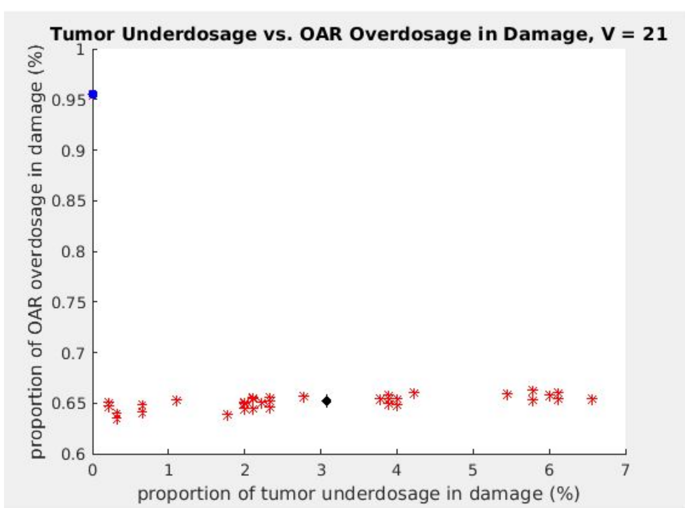



Figure 2: ATDM Tumor Underdosage vs OAR Overdosage, with lambda = 10mm and V = 21

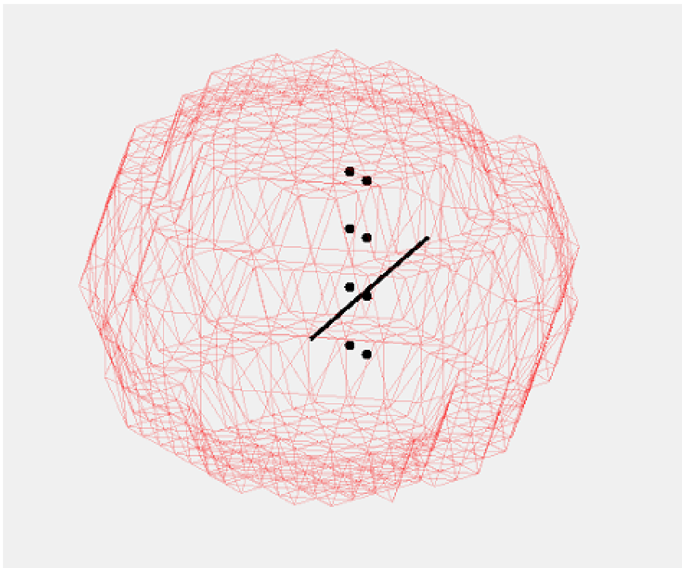


Figure 3: Potential Better Positions of Needle Insertion, with lambda = 7mm and V = 25

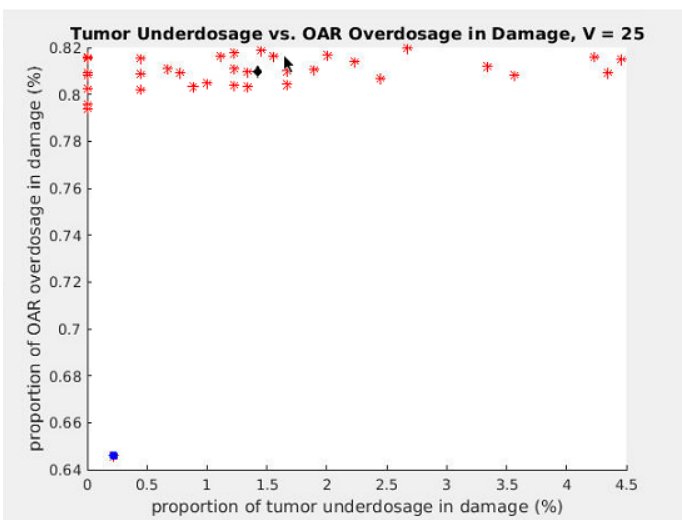



Figure 4: Tumor Underdosage vs OAR Overdosage, with lambda = 7mm and V = 25

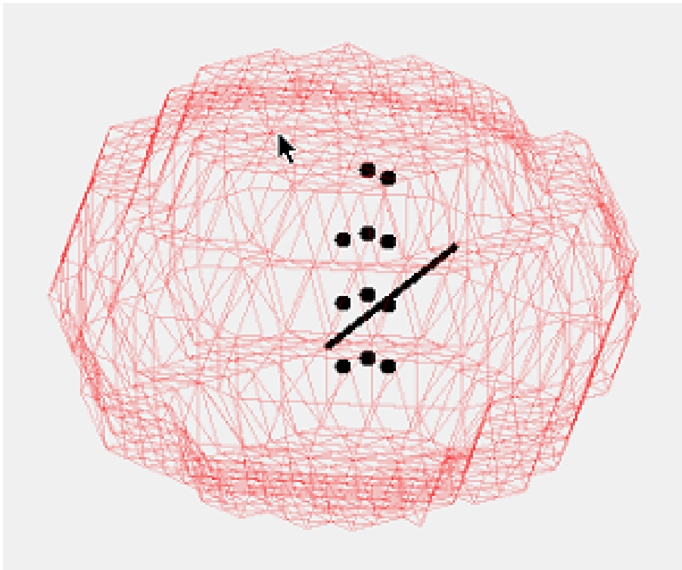


Figure 5: Potential Better Positions of Needle Insertion, with lambda = 7mm and V = 26

With a lambda of 7mm and initial voltage of 26V, the original position of needle insertion as well as 11 out of 35 deflected centers can ablate the tumor entirely, from the ATDM model. The position of these 11 deflected centers are shown in 5. The OAR damage of the original center is now 0.76%, and the deflected positions suffer 0.92% to 0.94% of OAR damage. This result suggests that when we use 26V as the initial voltage, there is some room for errors in insertion of the needle and the tumor can still be sufficiently ablated. As we increase the initial voltage to 30V, the tumor ablation will be complete for all 35 deflected positions.

### 5.3 Deflection

## 6 Discussion

## 7 Conclusion

Super sensitive to needle deflection

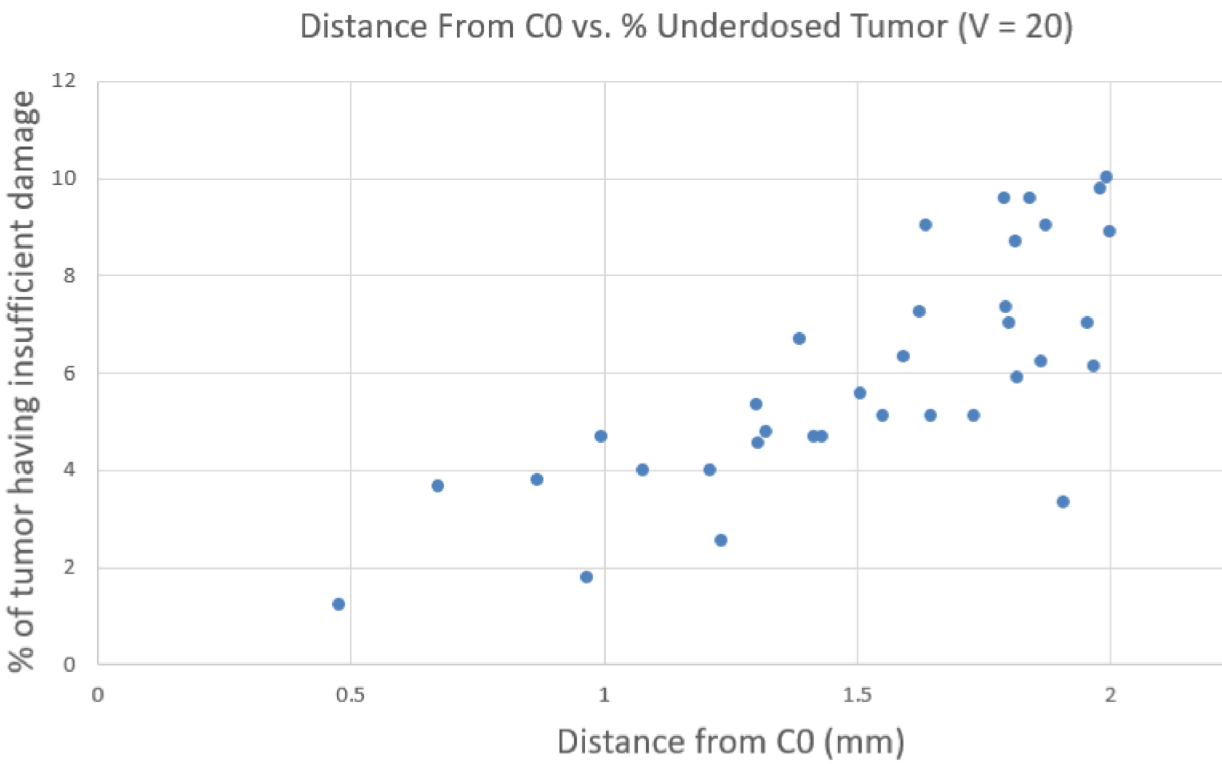



Figure 6: Figure

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