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# Active Denial Technology Computational Human Effects End-To-End Hypermodel (ADT CHEETEH)

## (Presentation)

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# Executive Summary

We developed the Active Denial Technology Computational Human Effects End-To-End Hypermodel (ADT CHEETEH), a computational model to simulate the response of a human target to Active Denial Technology (ADT), including estimates of ADT's physical, physiological, cognitive, and behavioral effects. The ADT system is a counter-personnel non-lethal weapon for crowd control, convoy protection, and perimeter security. The target is subjected to pulses of focused 95 GHz electromagnetic energy. The energy diffuses approximately 400 microns into the target's skin, producing no skin damage. However, the target may still perceive a burning sensation strong enough to repel (i.e., compel the target to immediately move away). We use one model component to estimate the physical output of the ADT system, coupled with three additional components to estimate the ADT's effect on the target's physiology, cognition, and behavior. All components passed verification tests. Validation data was available for only the physical component, which passed its validation test. Each run of ADT CHEETEH completes in only a few minutes on a standard laptop computer, beginning with a simulation of the ADT beam formation and concluding with the estimated time at which the target is repelled. This end-to-end approach quantifies the ADT system's main measure of effectiveness (the probability of repel) as well as its intermediate measures of performance (dose on target, temperature and damage in skin, perceived pain level, etc.) Once fully validated, ADT CHEETEH's comprehensive results may be able to feed into force-on-force simulations to provide educated estimates of ADT effectiveness in military scenarios.

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# Active Denial Technology Computational Human Effects End-To-End Hypermodel (**ADT CHEETEH**)

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S. Cazares et al. (2019) Active Denial Technology Computational Human Effects End-To-End Hypermodel (ADT CHEETEH). Presented at the *10th European Symposium on Non-Lethal Weapons*, Brussels Belgium, 20-24 May 2019.

# Challenges in Modeling Non-Lethal Weapons

| | Traditional (Lethal) Weapon | Non-Lethal Weapon |
|---|---|---|
| **Intended Use of Weapon:** | Permanently destroy target | Temporarily incapacitate target |
| **Goal of Model:** | Estimate weapon effect on target:<br>• Physical<br>• Physiological | Estimate weapon effect on target:<br>• Physical<br>• Physiological<br>• ***Cognitive***<br>• ***Behavioral***<br>Increased Variability & Uncertainty |

**Despite these challenges:**
**We developed an end-to-end computational model of a NLW system**

Computational models are often used to help design and test weapon systems.

Non-lethal weapons can be difficult to model. This is due to their inherent contrast with traditional, lethal weapons:

- The intended use of a traditional, lethal weapon is to permanently destroy the target. This means that models of traditional weapons must estimate the weapons' physical and physiological effects on targets.
- In contrast, the intended use of a non-lethal weapon is to temporarily incapacitate the target. The target remains alive, and, depending on the non-lethal weapon, he or she may still be able to think and act, even during the encounter. This means that non-lethal weapon models must estimate not only the weapons' physical and physiological effects on targets, but also their cognitive and behavioral effects.

Therein lies the challenge: A human's cognition and behavior are influenced by a large number of factors—so many factors that models of cognition and behavior often have a much higher variability and uncertainty than models of physics and physiology.

As a result, it can be difficult to fold together all four of these concepts into a single model, with their differing levels of variability and uncertainty.

Despite these challenges, we did just that: We developed an end-to-end computational model of a non-lethal weapon system, simulating the physical, physiological, cognitive and behavioral effects of a non-lethal weapon encounter on a human target.

# Active Denial Technology (ADT)

Photo By: Lance Cpl Andrew Huff (2017)


- **Counter-personnel NLW system:**
  - Crowd control
  - Patrol and convoy protection
  - Perimeter security
- **Emits short-duration pulses of focused 95 GHz electromagnetic energy**
- **Energy diffuses ≈400 microns into target's skin**
  - Produces **no skin damage** within appropriate range of doses
  - Elicits **burning sensation strong enough to repel**, i.e., to compel target to immediately flee

**The ADT system is a NLW system to stop, deter, and turn back suspicious individuals**

JNLWD (2016) Active Denial Technology Fact Sheet.
*https://jnlwp.defense.gov/Portals/50/Documents/Press_Room/Fact_Sheets/ADT_Fact_Sheet_May_2016.pdf*

We modeled a specific type of non-lethal weapon system: the Active Denial Technology system, or ADT.

ADT is a counter-personnel system intended for military missions in crowd control, patrol and convoy protection, and perimeter security (JNLWD 2016).

ADT systems emit short-duration pulses of focused electromagnetic energy (JNLWD 2016). They operate at a frequency of 95 GHz (JNLWD 2016). Because of their wavelength, ADT systems are often referred to as “millimeter wave technology”.

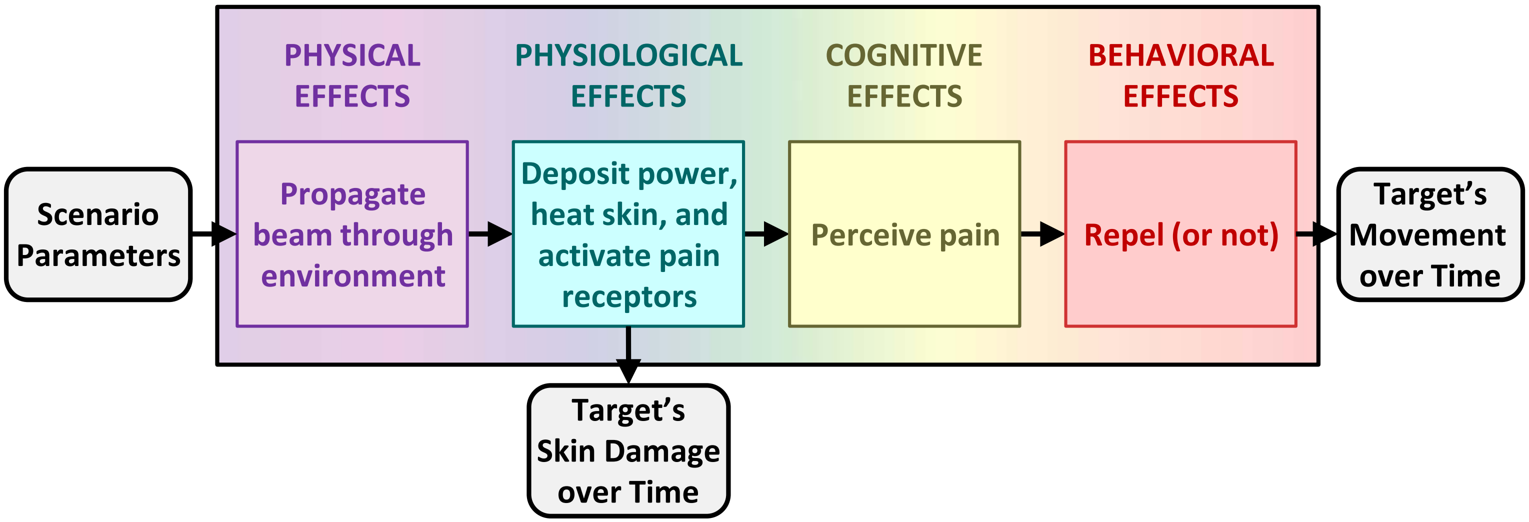
The ADT energy diffuses about 400 microns (1/64$^{th}$ of an inch) into the target’s skin (JNLWD 2016):

- This energy produces no skin damage, within an appropriate range of doses.
- However, this energy can elicit a burning sensation strong enough to repel—that is, to compel the target to immediately flee the area, as demonstrated by this document’s authors in a video of an ADT demonstration in the lower left.

The intended use of the ADT system is to stop, deter, and turn back suspicious individuals.

Thus the ADT system is an example of a weapon that produces physical, physiological, cognitive, and behavioral effects on human target.

**IDA ADT CHEETEH:** Active Denial Technology Computational Human Effects End-To-End Hypermodel




**ADT CHEETEH consists of four main components to model an ADT encounter with a human target**

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We created ADT CHEETEH, which stands for the Active Denial Technology Computational Human Effects End-To-End Hypermodel.

ADT CHEETEH is a computational model written in Python 3, an open-source coding language. Thus no software licenses are needed to run ADT CHEETEH.

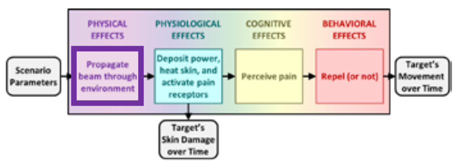
Each run completes in about two minutes on a standard laptop computer—and most of that time is spent writing the outputs to disk.

ADT CHEETEH consists of four main components—that is, four main blocks of code. The following slide will discuss each component in more detail. For now, though, note the inputs and outputs:

- Parameters describing the scenario are input into ADT CHEETEH—these scenario parameters describe the:
  - Environment (ambient temperature, pressure, humidity, rain rate, and so forth),
  - Target (skin parameters, pain tolerances, motivation, and so forth), and
  - ADT system (power, pulse duration, size, and so forth).
- Halfway through its calculations, ADT CHEETEH outputs an estimate of the target's skin damage over time—that is, over the few seconds since the start of the ADT pulse.
- At the end of its calculations, ADT CHEETEH outputs an estimate of the target's movement levels over time (did the target repel, and at what point since the start of the ADT pulse).

The next few slides discusses each of the four components.

# IDA ADT CHEETEH: Physical Effects



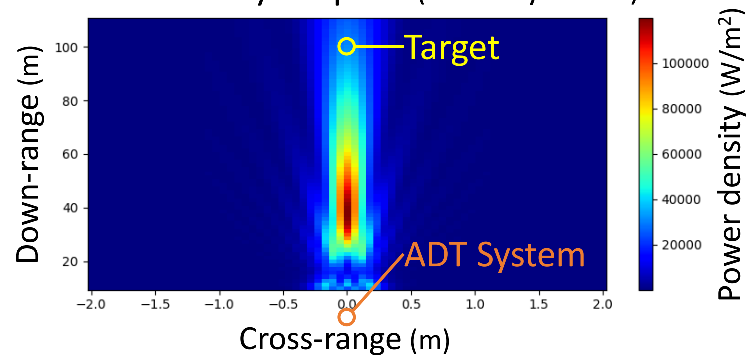

**What:** Power density in space and on target

**How:**

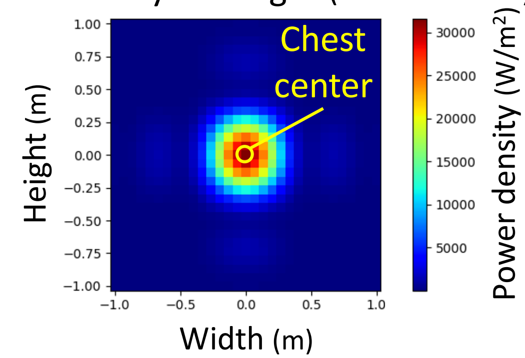
1. Treat ADT system as array of elements (Orfanidis 2002, Balanis 2005)
3. Estimate how energy propagates from each element through environment (Liebe 1993, Stutzman 2012)
3. Sum over all elements at target (Orfanidis 2002, Balanis 2005)

$$\boldsymbol{E}(\boldsymbol{r}) = \sum_{i=0}^{N-1} \beta_i \sqrt{2\eta_0 \wp_i} \frac{e^{\left(-\frac{\alpha}{2}R_i - jkR_i\right)}}{4\pi R_i} \boldsymbol{f}(\widehat{\boldsymbol{R}}_i), \quad P(\boldsymbol{r}) = \frac{|\boldsymbol{E}(\boldsymbol{r})|^2}{2\eta_0}$$

Power density in space (bird's eye view)




Power density on target (incident view)




**The ADT CHEETEH physical component estimates how the ADT power propagates through the environment**

The first component of ADT CHEETEH estimates the physical effects of the ADT system. This component estimates how the ADT power propagates through the environment to the target, outputting the ADT power density in space and on the target.

We coded up this component by treating the ADT system as an array of radiating elements (or current sources). We estimate how the energy propagates from each element through the environment, and then sum up that energy over all elements at the target.

In other words:

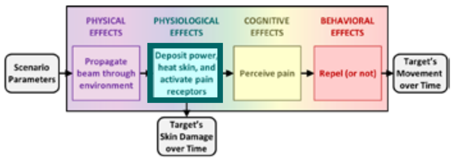
- In the first equation for **E**(**r**), we use the well-known Millimeter-wave Propagation Model (Liebe 1993) to estimate the atmospheric attenuation coefficient $\alpha$ based on published fits to experimental data. Then, we use the Field Equivalence Principal (e.g., Huygen's Approximation) (Orfanidis 2002, Balanis 2005) to discretize the ADT aperture into an array of N small elements. We model each small element i as a point source, such that we can use the Fraunhofer (e.g., Far-Field) Approximation (Stutzman 2012) to attenuate the electric field strength from each element by $\alpha$. Then we coherently sum the attenuated electric field strength at the target over all N elements, using the complex weights $\beta_i$ to take into account the phase differences between each element i.
- In the second equation for P(**r**), we calculate the power density on target from the amplitude squared of the electric field strength on target.

On the right, we show two plots of the output of this component:

- The upper right shows a bird's eye view of the ADT encounter. The ADT system is positioned at the origin (orange circle), and the x- and y- axes indicate the cross-range and down-range directions. The target is positioned 100 m directly down-range from the ADT system (yellow circle). The colors represent the power density emanating from the ADT system, with blue indicating lower values and red indicating higher values. In this particular run, the peak power density occurs at about 40 m down-range from the ADT system, in between the system and the target.
- The lower right shows the same data, but on a different plane—the surface of the target's chest. This time, the center of the target's chest (yellow circle) is positioned at the origin, and the x- and y- axes indicate the width and height dimensions of the target. The colors represent the power density incident on the surface of the target's chest—the dose-on-target.

Note that the two plots use different color scales.

# ADT CHEETEH: Physiological Effects (1 of 3)




**What:** Power density in skin

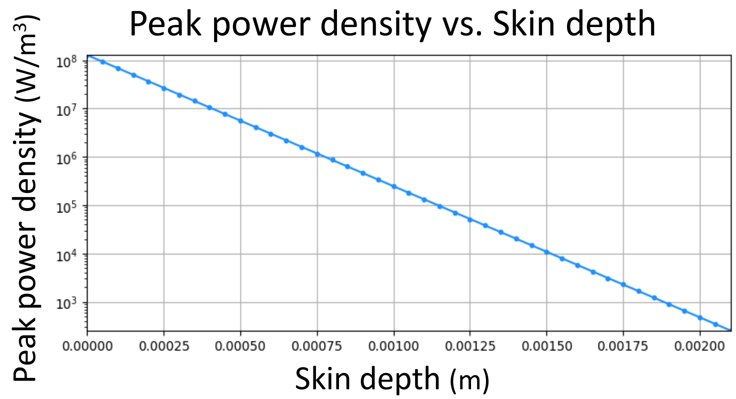
**How:**

1. Estimate how much incident power is reflected off of target's skin surface (Walters 2000)

$$P_{\text{dep}}(\boldsymbol{r}) = (1-\gamma)P(\boldsymbol{r})$$

2. Estimate how deep the remaining power deposits under target's skin surface (Welch 1995, Walters 2000)

$$q(\boldsymbol{r}, y) = \mu P_{\text{dep}}(\boldsymbol{r})e^{-\mu y}$$




**The ADT CHEETEH physiological component first estimates how the incident ADT power deposits into the target's skin**

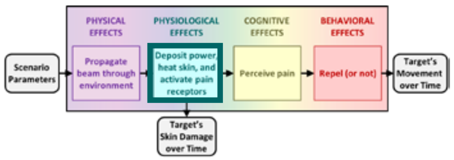
The second component of ADT CHEETEH estimates the physiological effects of the ADT system. We accomplish this in three steps, described on three different slides.

In the first step, the physiological component estimates how the ADT power—the dose-on-target from the previous slide—deposits into the target's skin:

- First, we estimate how much (i.e., what fraction) of the incident power—the dose-on-target—reflects off of the target's skin. In this version of ADT CHEETEH, we treat this reflected power as though it is completely lost to the air. We obtained a value for the skin reflectivity at 95 GHz from the literature (Walters 2000).
- Next, we estimate how deep the remaining power deposits under the target's skin surface. We use the Beer-Lambert Law for this calculation (Welch 1995). We obtained a value for the skin absorption coefficient at 95 GHz from the literature (Walters 2000).

On the right, we show a plot of the peak power density in the skin versus skin depth. As expected, the plot shows a log-linear relationship.

# ADT CHEETEH: Physiological Effects (2 of 3)




**What:** Temperature and damage in skin

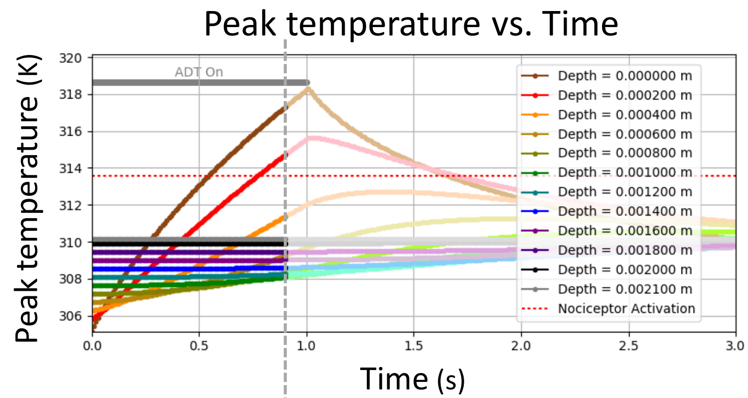
**How:**

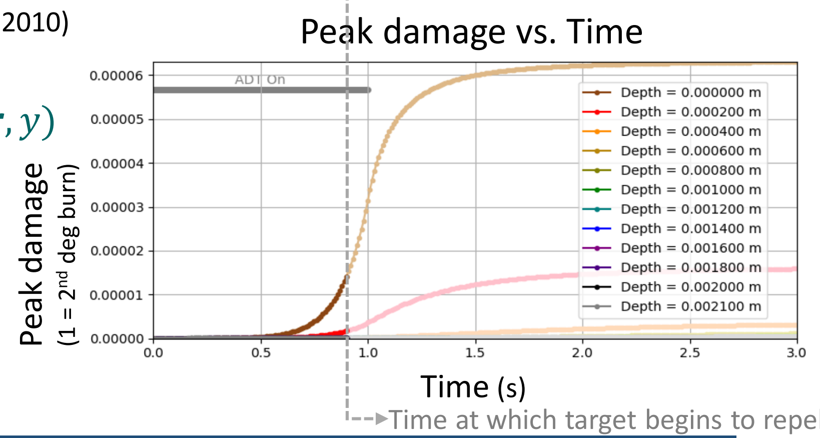
1. Estimate how fast and deep heat transfers through target's skin (Fourier 1822, Cannon 1984, Haberman 1983, Rushmer 1966, Koehler 1996, Xu 2010)

$$\rho C_p \frac{\partial T(\boldsymbol{r},y,t)}{\partial t} = \frac{\partial}{\partial y}\left(K \frac{\partial T(\boldsymbol{r},y,t)}{\partial y}\right) + q(\boldsymbol{r},y)$$

2. Estimate how much the heat destroys proteins in target's skin (Henriques 1947, Pearce 2010)

$$\Omega(\boldsymbol{r},y,t) = \int_0^t A e^{\left(\frac{-E_a}{R\,T(\boldsymbol{r},y,\tau)}\right)} d\tau$$




**The ADT CHEETEH physiological component then estimates how heat transfers through the target's skin and (possibly) causes damage**

The physiological component also estimates how fast and deep the heat transfers through the target's skin, and how much that heat destroys the proteins in the target's skin (if at all).

We use the one-dimensional Fourier Heat Equation (Fourier 1822, Cannon 1984, Haberman 1983) to simulate the transfer of heat longitudinally into the skin. The transverse dispersion of heat radially through the skin is much slower and so we ignore it. We obtain values for the boundary conditions—the temperature of the backwall fat and initial skin surface—from the literature (Rushmer 1966, Koehler 1996). We also obtain values for the skin density $\rho$, specific heat capacity $C_p$, and thermal conductivity $K$ of each layer of skin (epidermis, dermis, and so forth) from the literature (Xu 2010).

We use the Arrhenius Equation (Henriques 1947) to estimate the damage to the skin. We use values from the literature to calibrate the coefficients of this equation such that damage = 1 indicates the onset of a second-degree burn (Pearce 2010).

On the upper right, we show a plot of the peak temperature in the target's skin over time, from the start of the ADT pulse at 0 seconds to 3 seconds after that:

- Each colored trace represents a different depth below the skin surface. For example:
  - The brown trace represents the peak temperature at the surface of the skin (a depth of 0).
  - The red trace represents the peak temperature 200 microns under the surface of the skin.
- The horizontal grey bar marks the duration of the ADT pulse—in this particular run, it was set to 1 second. The user can adjust this value.
- At any given depth, the target's skin temperature rises over time, and then begins to drop as soon as the ADT pulse turns off, at 1 second. However, that heat doesn't disappear immediately, and so it does take time for the temperature in the skin to come back down to normal.
- The color of the traces switches from dark to light at around 0.9 seconds. We'll see later that this is the point in time at which ADT CHEETEH estimates that the target begins to flee the area. Once he flees, the dose-on-target changes, and so any calculations after this point are not intended to be valid. We still plot them, though, to give a hypothetical idea of what the outputs would be, if the target were physically confined and not allowed to flee—an imaginary, worse-case scenario.

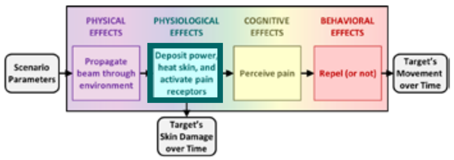
On the lower right, we plot the peak damage in the target's skin over that same time scale:

- Once again, each colored trace represents a different depth below the skin surface.

- In this particular run, the skin damage does not begin to occur until around 0.5 seconds.
- Interestingly enough, the peak damage does not reach its maximum level until around 2 seconds, well after the ADT pulse has turned off—in the hypothetical case that the target was physically constrained and not allowed to flee, that is. According to a later component of the model, though, the target does flee, much earlier at 0.9 seconds.
- Furthermore, even if the target did not flee, the light-colored parts of the traces show that the maximum damage is extremely low, close to zero. We tuned our model such that a value of 1 on the y-axis indicates the onset of second-degree burn. Here, the y-values are much, much less than 1, indicating that the damage is much, much less severe—hardly no damage at all.

This damage over time is one of the key outputs of ADT CHEETEH.

# ADT CHEETEH: Physiological Effects (3 of 3)

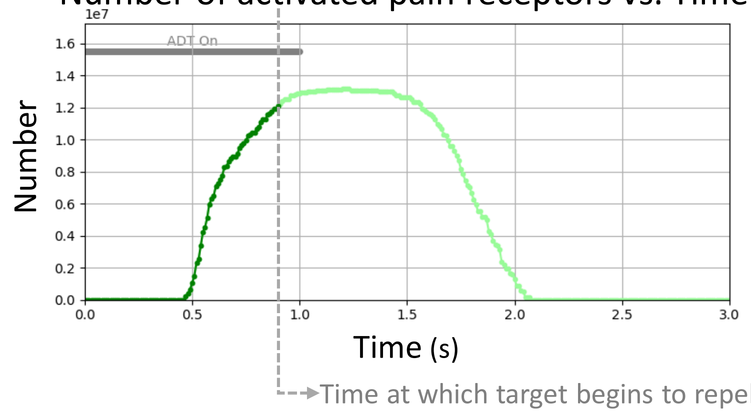



**What:** Number of activated pain receptors

**How:**

1. Treat skin as collection of voxels (3D pixels)
2. Estimate number of pain receptors in each voxel, based on their density (Ochoa 1969, Schmidt 1995, Tillman 1995, McArthur 1998, Sandby-Moller 2003)
3. Estimate average temperature of each voxel
4. If voxel's average temperature ≥ threshold (Tillman 1995), then assume all pain receptors are activated in voxel
5. Sum over all voxels

Number of activated pain receptors vs. Time




$$x_i(t) = \begin{cases} V_i \rho_{\text{noc}}, & if\ \bar{T}_i(t) \geq T_{\text{act}} \\ 0, & if\ \bar{T}_i(t) < T_{\text{act}} \end{cases}$$

$$x(t) = \sum_{i=0}^{M-1} x_i(t)$$

**The ADT CHEETEH physiological component also estimates how many pain receptors become activated in the target's skin**

The physiological component also estimates how many pain receptors become activated in the target's skin, due to the rise in temperature.

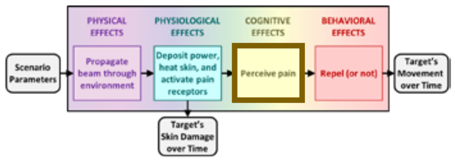
We treat the skin as a collection of voxels—that is, 3D pixels. The user can set parameters that define the volume of the voxels—our default is about 30 cubic mm to enable fast computation:

- We estimate the number of pain receptors in each voxel, based on the density of pain receptors in human skin, $\rho_{noc}$—an input parameter that the user can set. We allow the density to vary with skin depth. We obtain values for the nociceptor density $\rho_{noc}$ at different skin depths from a careful search of the literature for heat-sensitive C-fibers (McArthur 1998, Ochoa 1969, Schmidt 1995, Tillman 1995, McArthur 1998, Sandby-Moller 2003).
- We also estimate the average temperature of each voxel over time, based on the outputs of the Fourier Heat Equation discussed in the previous slide.
- At any given time point, if the voxel's average temperature is greater than an activation threshold $T_{act}$, then we assume that all pain receptors are activated in that voxel. The user can set the temperature activation threshold $T_{act}$. We obtain a value for this threshold from the literature (Tillman 1995). (Note that this threshold was plotted as a dotted red line on the top plot of the previous slide.)
- We sum up over all voxels, and plot the results on the right.

On the right is a plot of the number of activated pain receptors in the assessed skin over the same time period shown in previous slides:

- We see that nociceptors do not begin to become activated until around 0.5 seconds, after which their number continues to rise until the ADT pulse turns off.
- They maintain a plateau for about 0.5 seconds, and then begin to deactivate.

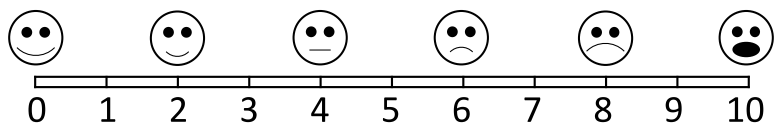
# ADT CHEETEH: Cognitive Effects

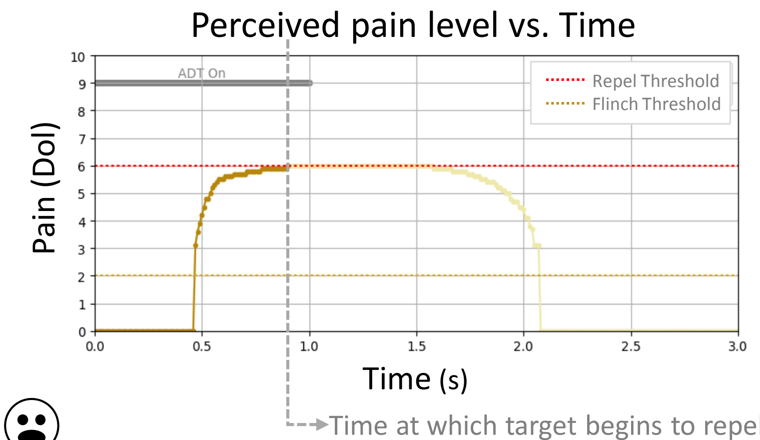



**What:** Perceived pain level

**How:**

1. Measure pain on Dol scale (Hardy 1947, 1948):




2. Translate number of activated pain receptors to perceived pain level, based on S-shaped curve fit to data in scientific literature (Hardy 1947, Mouraux 2012)

$$y(t) = \frac{a}{1 + e^{-\left(\frac{\log(x(t)) - b}{c}\right)}}$$

**The ADT CHEETEH cognitive component estimates the target's perceived pain level**

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We are now halfway through our description of ADT CHEETEH. So far, we have described how ADT CHEETEH estimates the physical and physiological effects on the target. Now, we turn our attention to the cognitive and behavioral effects.

The cognitive component of ADT CHEETEH estimates the target's perceived pain level.

We quantify pain with the Dol scale (Hardy 1947, 1948):

- The Dol scale is often used in hospitals to help doctors and nurses determine how much pain a patient is reporting.
- The Dol scale ranges from 0 to 10, where:
  - 0 indicates no pain,
  - 1 indicates the first twinge of pain, and
  - 10 indicates the worse pain imaginable.
- The Dol scale is a quantitative metric of a subjective experience—pain. Perceived pain varies from person to person, and within the same person over time. Studies have shown, though, that the maximum intra- and inter-observability of perceived pain is only +/- 2 Dols (Hardy 1948), with most scatter only +/- 1 Dol from the average report.

We translate the number of activated pain receptors to a perceived pain level in Dols, based on an S-shaped curve that we fit to data in the scientific literature:

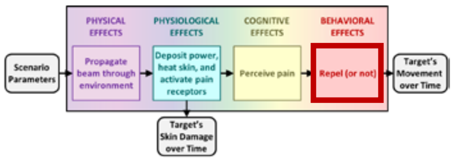
- There aren't many data out there on ADT encounters.
- Therefore we fit our data to the next best thing—reports of pain perceptions of radiant heat applied to the surface of the skin:
  - First, we extrapolated from the literature (Mouraux 2012) to set one point of our S-shaped curve: the number of nociceptors (on the x-axis) that would provide a 1 Dol report (on the y-axis), the first twinge of pain.
  - From there, we set the rise rate c of our S-shaped curve to match the shape of a similar curve in the literature (Hardy 1947).

On the right, we plot perceived pain level over time:

- No pain occurs until around 0.5 seconds, which, as we saw in the previous slide, was the same point in time at which pain receptors begin to be activated.

- The pain rises quite sharply and hits its maximum level of just past 6 Dols, even before the ADT pulse turns off.
- We plot a red horizontal line on this plot, indicating an average person's pain tolerance threshold. Below this threshold, the target remains in place, and beyond this threshold, the target repels. This threshold is a parameter that the user can set. In this particular run, it was set to exactly 6, based on our interpretation of the literature (Xu 2008, Plaghki 2010, Short 2010, Moreno 2012, Mouraux 2012).

## ADT CHEETEH: Behavioral Effects

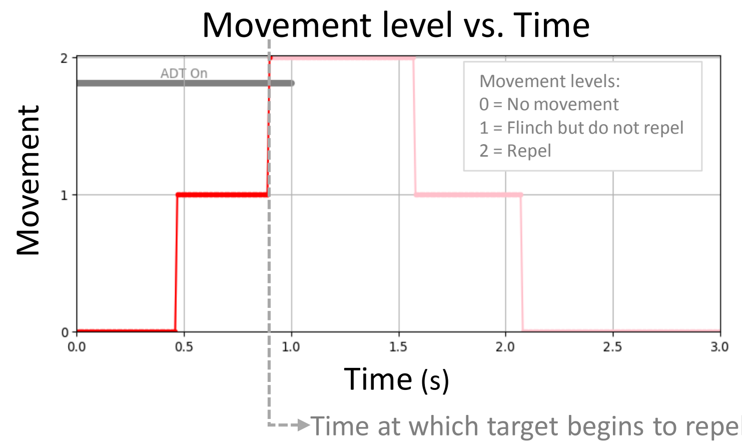



**What:** Movement levels over time

0 = no movement

1 = flinch but do not repel

2 = repel




**How:**

1. Modulate perceived pain level based on motivation
2. Compare motivation-modulated pain to pain tolerance thresholds (Xu 2008, Plaghki 2010, Short 2010, Moreno 2012, Mouraux 2012)

$$y'(t) = y(t) - \frac{m}{m_0}$$

$$g(t) = \begin{cases} 0, if\ y'(t) < Y_{\mathrm{lo}} \\ 1, if\ y'(t) \geq Y_{\mathrm{lo}}\ and\ y'(t) < Y_{\mathrm{hi}} \\ 2, if\ y'(t) \geq Y_{\mathrm{hi}} \end{cases}$$

**The ADT CHEETEH behavioral component estimates when the target (possibly) repels**

Finally, the ADT CHEETEH behavioral component estimates if and when the target repels.

We quantify the target's movement levels on a 3-point scale:

- 0 indicates no movement
- 1 indicates the target flinches but does not repel
- 2 indicates the target repels
-

In this component, we first take the target's motivation level into consideration. Motivation *m* is another parameter that the user can adjust, on a Likert-like scale ranging from -2 to 2. We use a default value of 0 to indicate neutral motivation.

We then compare the target's motivation-modulated pain to the pain tolerance threshold $Y_{\mathrm{hi}}$ plotted as a dotted red line on the previous slide.

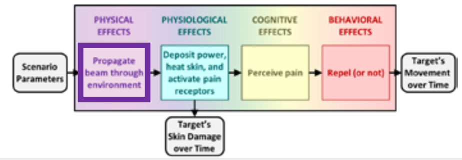
On the right we plot the target's movement levels over time:

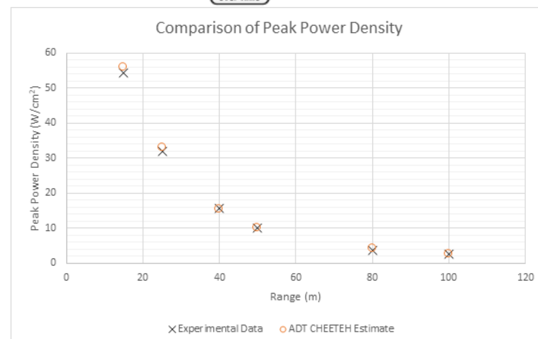
- The target did not flinch until around 0.5 seconds—the same point in time at which his pain receptors become activated and his perceived pain level begins to rise.
- The target repels at around 0.9 seconds—this is the point in time at which all traces in the previous slides switched from dark to light colors.

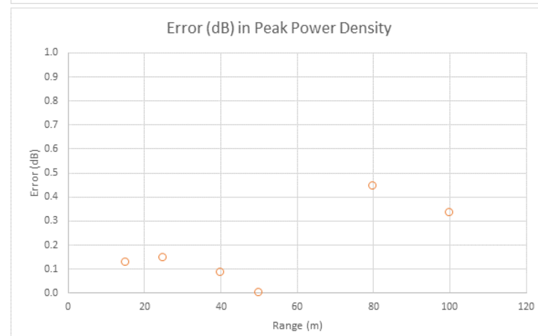
This is the final output parameter of ADT CHEETEH.

## ADT CHEETEH: Verification & Validation

- **Verification:** Full
  - Compared manual vs. model calculations for all output parameters
  - All errors ≈0
- **Validation:** Partial
  - Validation data was only available for output parameter of physical component – ***power density on target***:
    - **ADT CHEETEH estimates were within 0.5 dB of experimental data**
    - We conclude the ADT CHEETEH physical component passed its validation test
  - We are exploring opportunities to obtain validation data for the three other ADT CHEETEH components




Biddle et al. (2018) *Beam Propagation Model Selection for Millimeter-Wave Directed Energy Weapons*. Presented at the Directed Energy Systems Symposium, 24-27 Sept 2018.

**Full validation of ADT CHEETEH is necessary and on-going**

Of course, a model is only as good as its verification and validation.

We fully verified all four components of ADT CHEETEH. To do this, we:

- Manually calculated the different outputs we plotted on the previous slides, for several corner cases and
- Compared our manual calculations to the outputs of ADT CHEETEH.
- All errors were very close to zero, with several significant digits.

So far, we have only partially validated ADT CHEETEH (Biddle 2018):

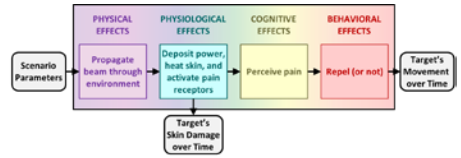
- Validation data was only available for one output parameter—the power density on target that is output by the first component.
- We compared ADT CHEETEH's peak power density outputs to measured, experimental data at several ranges, as shown on the top plot.
- As shown on the bottom plot, errors were less than 0.5 dB, over all ranges.
- Therefore we conclude that the ADT CHEETEH physical component passed its validation test.

We are exploring opportunities to obtain validation data for the three other model components, including:

- FLIR cameras to obtain temperature data on the surface of the target's skin,
- Surveys to obtain the target's maximum perceived pain level, and
- Triggered timers or video to obtain the times at which the target repels.

In short, full validation of ADT CHEETEH is necessary and on-going.

# ADT CHEETEH: Sensitivity Analysis




- **Purpose:** Identify to which factors of a scenario is ADT CHEETEH most sensitive
- **Methods:**
  - Vary individual input parameters over ±1 standard deviation
  - Examine ADT CHEETEH's final output parameter – movement level over time
  - Identify those input parameters whose variation caused the movement level to "max out" at all three possible values (0, 1, or 2)
- **Results:** Four noteworthy input parameters:
  - ***ADT pulse duration*** – in control of ADT system developers
  - ***Target's skin surface reflectivity*** – subject to natural variation in target population – well understood
  - ***Temperature threshold at which pain receptors activate*** – subject to natural variation in target population – partly understood
  - ***Density of pain receptors*** – subject to natural variation in target population – not well understood in this context

**Once validated, ADT CHEETEH could help prioritize which factors of an ADT encounter could benefit from further research**

In the meantime, though, we took a closer look at the different input parameters to ADT CHEETEH, in order to determine to what factors of a scenario ADT CHEETEH most sensitive:

- We performed thousands of runs of ADT CHEETEH, each time varying an individual parameter.
- All in all, we varied each individual parameter over +/- 1 standard deviation.
- For each run, we examined ADT CHEETEH's final output parameter—the target's movement level over time—0 for no movement, 1 for flinch but do not repel, and 2 for repel.
- We then identified those input parameters whose variation caused the movement level to "max out" at all three possible values—these were the most noteworthy parameters of our analysis.

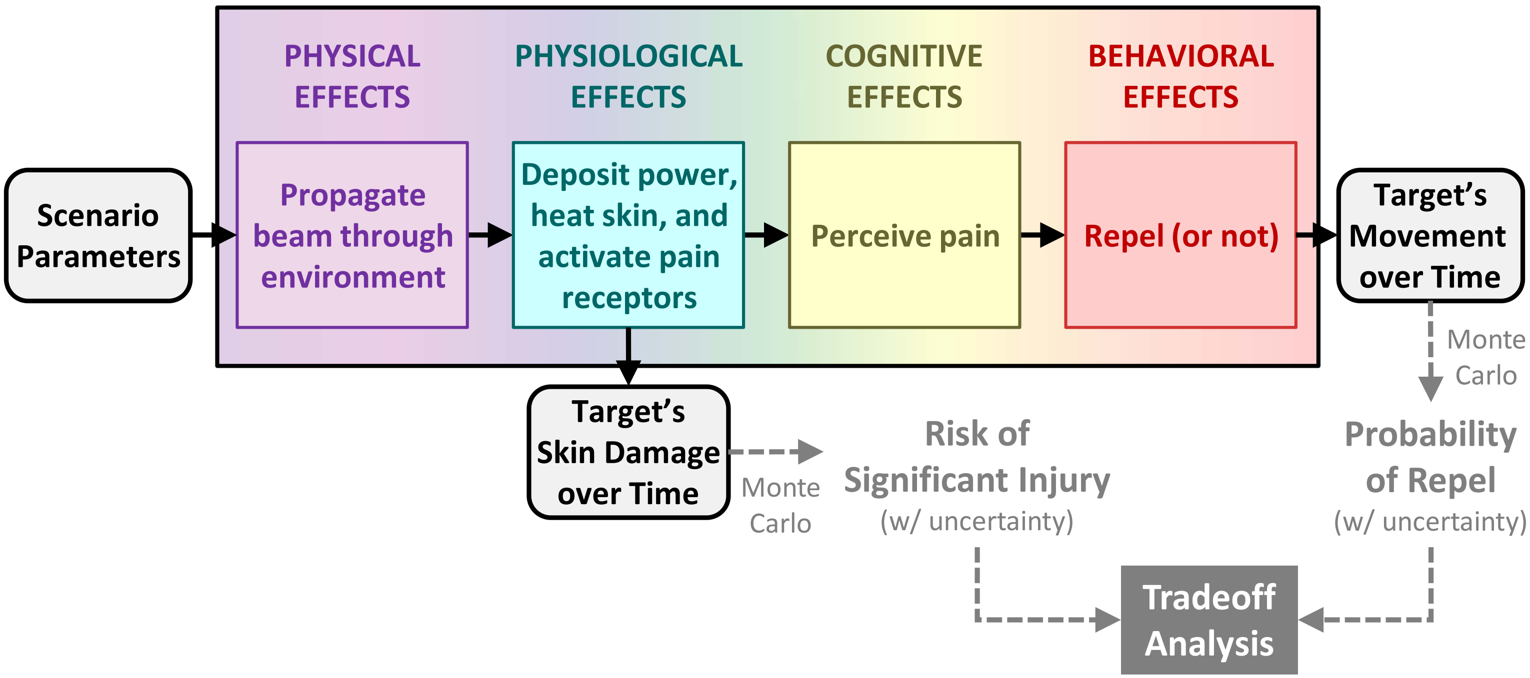
We found four noteworthy parameters:

- The ADT pulse duration (horizontal grey bars in figures on slides 7–10): This parameter is in control of the ADT system developer—he or she can explicitly consider this parameter when designing systems to achieve the desired level of effectiveness.
- The target's skin reflectivity ($\gamma$ in top equation on slide 6): This parameter is not in control of the ADT system developer, and is subject to the natural variation of the target population. Fortunately, scientists have characterized this variation. Laboratory studies (Walters 2000) have determined the distribution of human skin's reflectivity at ADT frequencies. ADT system developers can therefore use these experimental data to design systems that achieve the desired effectiveness despite the natural variation in skin reflectivity.
- The temperature threshold at which pain receptors activate ($T_{act}$ in the top equation of slide 8): This parameter is also subject to the natural variation in the target population. This factor is only partially understood, however (Tillman 1995).
- The density of pain receptors in human skin ($\rho_{noc}$ in the top equation of slide 8): Once again, this parameter is subject to the natural target population variation. This parameter is poorly understood in this context (McArthur 1998, Ochoa 1969, Schmidt 1995, Tillman 1995, McArthur 1998, Sandby-Moller 2003).

Thus both the temperature activation threshold $T_{act}$ and pain receptor density $\rho_{noc}$ are two input parameters that provide the widest sources of variability to ADT CHEETEH *and* that are the least understood in this context. Thus further research is warranted on these two input parameters.

Once validated, results of ADT CHEETEH sensitivity analyses could help prioritize which factors of an ADT encounter could benefit from further research.

# IDA ADT CHEETEH: Monte Carlo Plans




**Once validated, ADT CHEETEH could be used to explore the trade space between Risk of Significant Injury and Probability of Repel**

As shown on the previous slides, ADT CHEETEH has many input parameters that describe different aspects of the ADT scenario:

- Environmental factors—ambient temperature, pressure, humidity, range rate, and so forth
- Target characteristics—skin parameters, pain tolerances, motivation, and so forth
- ADT system design specifications—power, pulse duration, size, and so forth

The user can adjust the input parameters however he or she wants. We have reviewed the literature to compile a set of default parameter values, which is available upon request, with permission of the JNLWD.

ADT CHEETEH is a deterministic model—for any given combo of input parameters, ADT CHEETEH always returns the same output parameters.

However, we can use mathematical techniques called Monte Carlo simulations, on top of ADT CHEETEH, to get a sense of the variability and uncertainty around the ADT output parameters:

- Each run of ADT CHEETEH takes only about one to two minutes on a standard laptop computer.
- Thus we can easily run thousands of runs of ADT CHEETEH, varying the input parameters across known distributions of environmental parameters, human skin parameters, and so forth.
- Then, we can compile the two main outputs of ADT CHEETEH into the two main metrics that are used in the United States Department of Defense to describe the performance of any given non-lethal weapon system. Specifically:
  - We can translate the damage outputs into a probabilistic Risk of Significant Injury metric.
  - We can translate the movement outputs into a Probability of Effect (i.e., Repel) metric.
- Finally, we can compare these metrics to each other to map out the trade space between Risk of Significant Injury and Probability of Repel.

## Conclusion

- ADT CHEETEH is a **computational, end-to-end model** of the physical, physiological, cognitive, and behavioral effects of the ADT system on a human target
- All four components of ADT CHEETEH **passed all verification tests** (errors ≈0)
- Validation data was only available for the physical component model:
  - The **physical component passed its validation test** (errors < 0.5 dB)
  - We are exploring opportunities for obtaining data to validate the other components (using FLIR cameras, pain surveys, triggered timers/video, etc)
- We used ADT CHEETEH to **explore the most noteworthy factors** in an ADT encounter
  - Some within control of the ADT system designer (pulse duration)
  - Others subject to natural variation in target population (skin reflectivity, temperature activation threshold, pain receptor density)
- Once validated, ADT CHEETEH could **support force-on-force simulation software**:
  - Simulations have friendly, opposing, and neutral forces with variable weapon sets
  - Data tables stipulate a weapon's Probability of Effect on a target
  - ADT CHEETEH could be used to build data tables to simulate ADT effects

In conclusion:

ADT CHEETEH is a computational, end-to-end model of the physical, physiological, cognitive, and behavioral effects of the ADT system on a human target.

All four components of ADT CHEETEH passed all verification tests, with errors equal to zero within several significant digits.

Validation data was only available for the physical component model, that which estimates the power density on target:

- This component passed its validation test, with errors less than 0.5 dB.
- We are exploring opportunities for obtaining data from FLIR cameras, pain surveys, and triggered timers or video analysis to validate the other components.

In the meantime, we used ADT CHEETEH to explore the most noteworthy factors in an ADT encounter:

- Some which are under control of the ADT system designer, such as ADT pulse duration.
- Others which are not, such as skin reflectivity, temperature activation threshold, and pain receptor density.

Finally, once validated, ADT CHEETEH could be used to support other software simulation packages, such as force-on-force simulation software:

- These simulations have friendly, opposing, and neutral forces with variable weapon sets.
- The simulations use data tables to stipulate any given weapon's Probability of Effect on a given target.
- Current data tables are not yet accurate and precise enough to simulate non-lethal weapons effects.
- Once validated, ADT CHEETEH could be used to build more high-fidelity data tables to simulate ADT effects.
- This capability would allow military commanders to get a better sense of how ADT could support a more traditional arsenal of lethal weapons, providing for a more gradual escalation in force in different military missions.

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## IDA Questions?

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

We developed a computational model to simulate the response of a human target to Active Denial Technology (ADT), including estimates of ADT's physical, physiological, cognitive, and behavioral effects. The ADT system is a counter-personnel non-lethal weapon for crowd control, convoy protection, and perimeter security. The target is subjected to pulses of focused 95 GHz electromagnetic energy. The energy diffuses approximately 400 microns into the target's skin, producing no skin damage. However, the target may still perceive a burning sensation strong enough to repel (i.e., compel the target to immediately move away). The ADT system differs from traditional, lethal weaponry. The goal of a lethal weapon is to permanently destroy the target—therefore, models of lethal weaponry must simply estimate the weapon's physical and physiological effects. In contrast, the goal of the ADT system is to temporarily repel the target—therefore, ADT models must also estimate the ADT's cognitive and behavioral effects. We use validated physical models to estimate the output of the ADT system, coupled with additional models to estimate the ADT's effect on the target's physiology, cognition, and behavior. Our model begins with ADT beam formation and concludes with the estimated time at which the target is repelled. This end-to-end approach quantifies both the ADT system's main measure of effectiveness (the probability of repel) as well as its intermediate measures of performance (dose on target, temperature in skin, perceived pain level, etc.). These comprehensive model results may feed into force-on-force simulations to provide educated estimates of ADT effectiveness in military scenarios.

15. SUBJECT TERMS

95 GHz; Active Denial Technology (ADT); millimeter-wave; modeling and simulation (M&S); repel

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