CT dose measurements in cylindrical phantoms: Where are we headed?

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Acknowlegements

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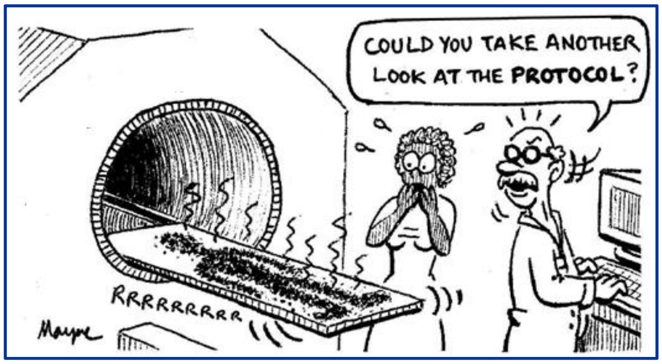
It may not always be a good idea to investigate radiation dose clinically



So perhaps we should try to learn what we can from phantoms

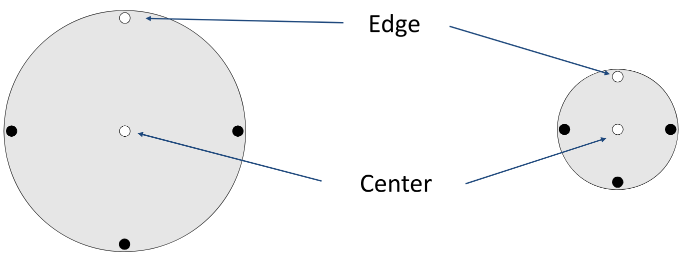
$CTDI_{vol}$ Dose Phantoms and Chamber

Defining Article: Shope, T., R. Gagne, and G. Johnson. (1981). "A method for describing the doses delivered by transmission x-ray computed tomography." *Med Phys* 8:488–495.

$CTDI_{VOL}$, the Weighted Average—Includes *Pitch*

(intended to be spatial average over central cross section of the phantom)

$$CTDI_{VOL} = (2/3\ CTDI_{100,edge} + 1/3\ CTDI_{100,center})/p$$



Concept related to pitch in article by Shope, Gagne and Johnson (SGE)

- In SGE, CTDI (infinite scan) is defined for axial scans with the beam width T equal to increment I.
- MSAD (Multiple Scan Average Dose) shown to be equal to CTDI if $I = T$.
- $If\ I \neq T$, then $\text{MSAD}(T,I) = (T/I) \times \text{CTDI}$.

This is close to how we account for pitch today:

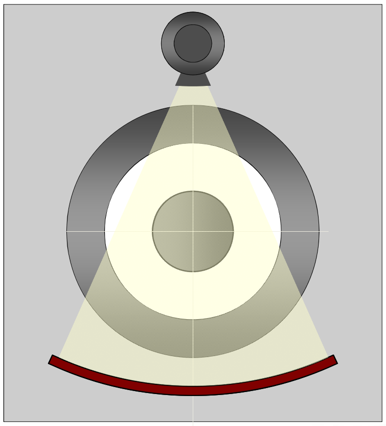
$\text{CTDI}_{\text{vol}} = \text{CTDI}_{\text{w}}/\text{pitch}$ (where pitch is essentially I/T.

Defining Article: Shope, T., R. Gagne, and G. Johnson. (1981). "A method for describing the doses delivered by transmission x-ray computed tomography." *Med Phys* 8:488–495.

For the time being, confine discussion to a cylinder of infinite length

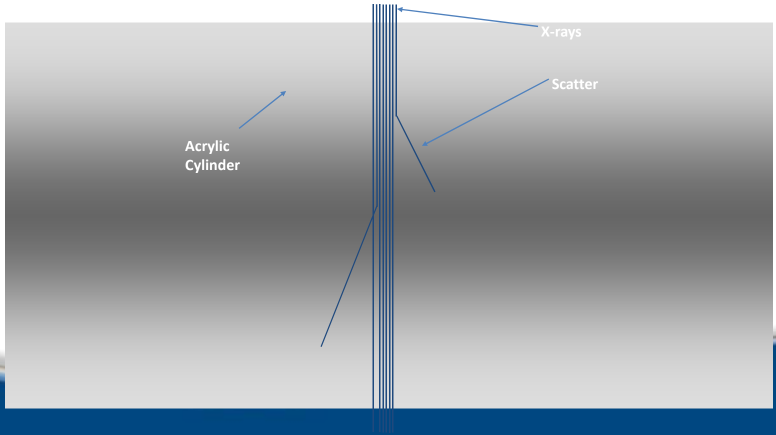
How are the x-rays delivered in CT?

We require projections from all angles
(or at least 180° plus fan angle)



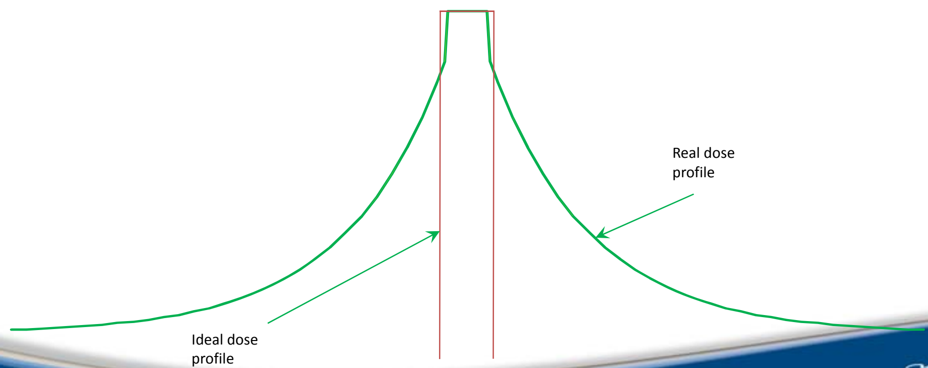
What is the Dose Profile?

Looking at our plastic cylinder from the side, we can see that scattered x-rays contribute to the dose outside of the direct beam.



Dose Profile

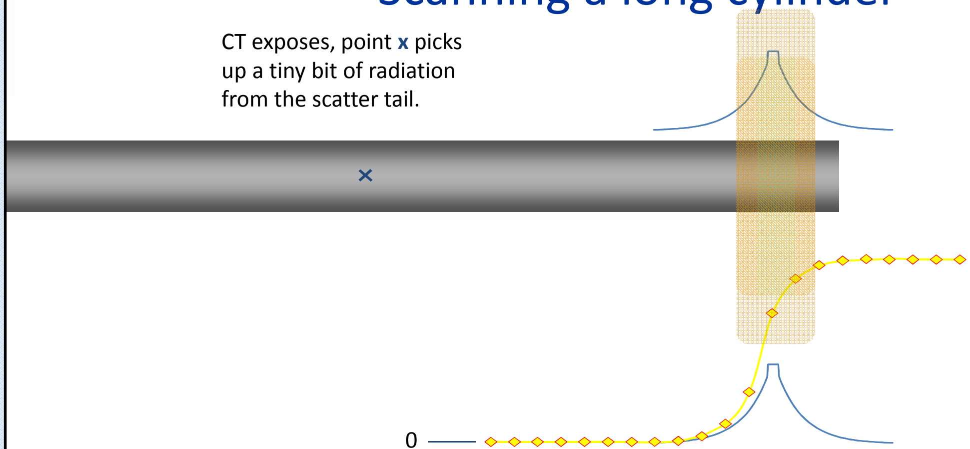
Because of scatter, the dose profile can extend well beyond the nominal collimated beam width *a*.



Based on data from TG200 very long phantom measurements.

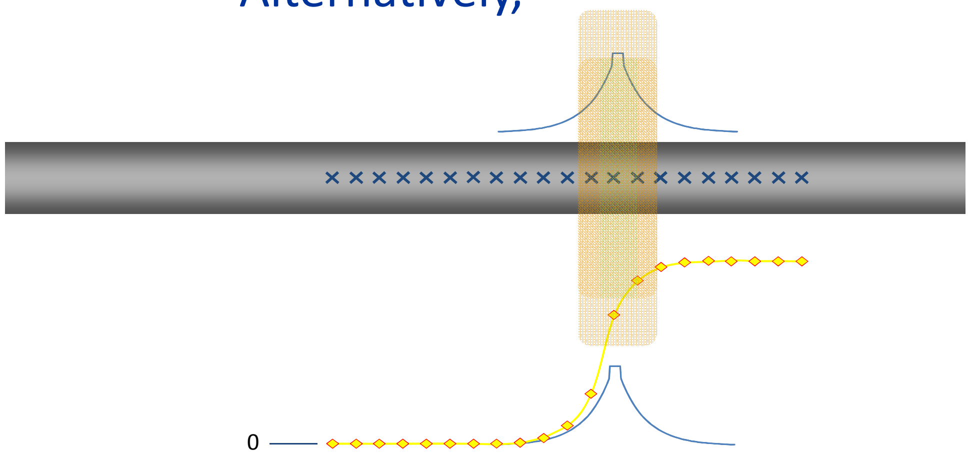
Scanning a long cylinder

CT exposes, point **x** picks up a tiny bit of radiation from the scatter tail.



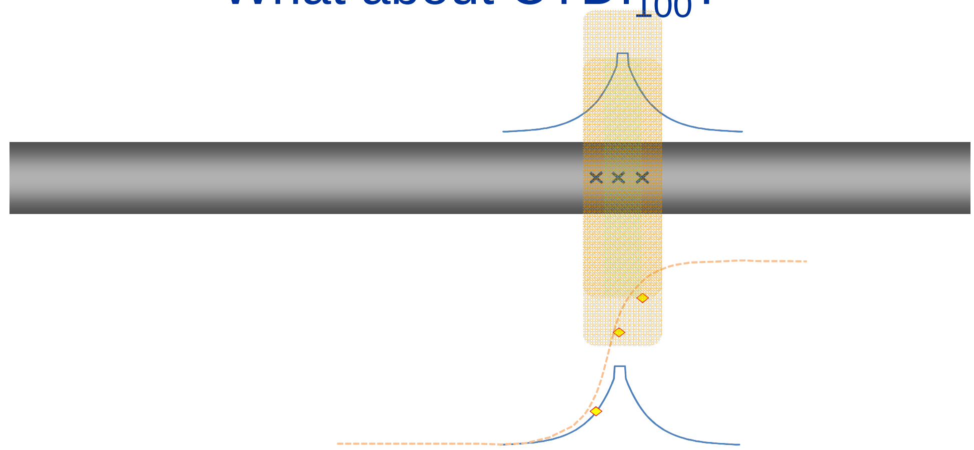
Note: Note that if the scans are closer together, the ultimate dose will be higher. Although an axial scan is depicted, the extension of the concept to helical scans is obvious.

Alternatively,



one could perform only one axial exposure with the phantom not moving and measure the dose at points all along the dose profile. Then add all these individual doses together. (In order to make the total come out the same, the distance between the individual dose measurements would be the same as the table movement per rotation of the slide shown earlier.) Alternatively, use a really long skinny ion chamber.

What about $CTDI_{100}$?



The chamber normally used is 100 mm long. It is not long enough to capture the entire dose profile and leaves off the tails. Thus, as you can see, the cumulative value is less than would be for an infinite scan. When we use a pencil chamber that is too short to capture the entire profile, the CTDI value we get is equivalent to that for a scan that is the length of the chamber. For a 100 mm chamber, we get $CTDI_{100}$.

Henry Ford Health System

So how does this work?

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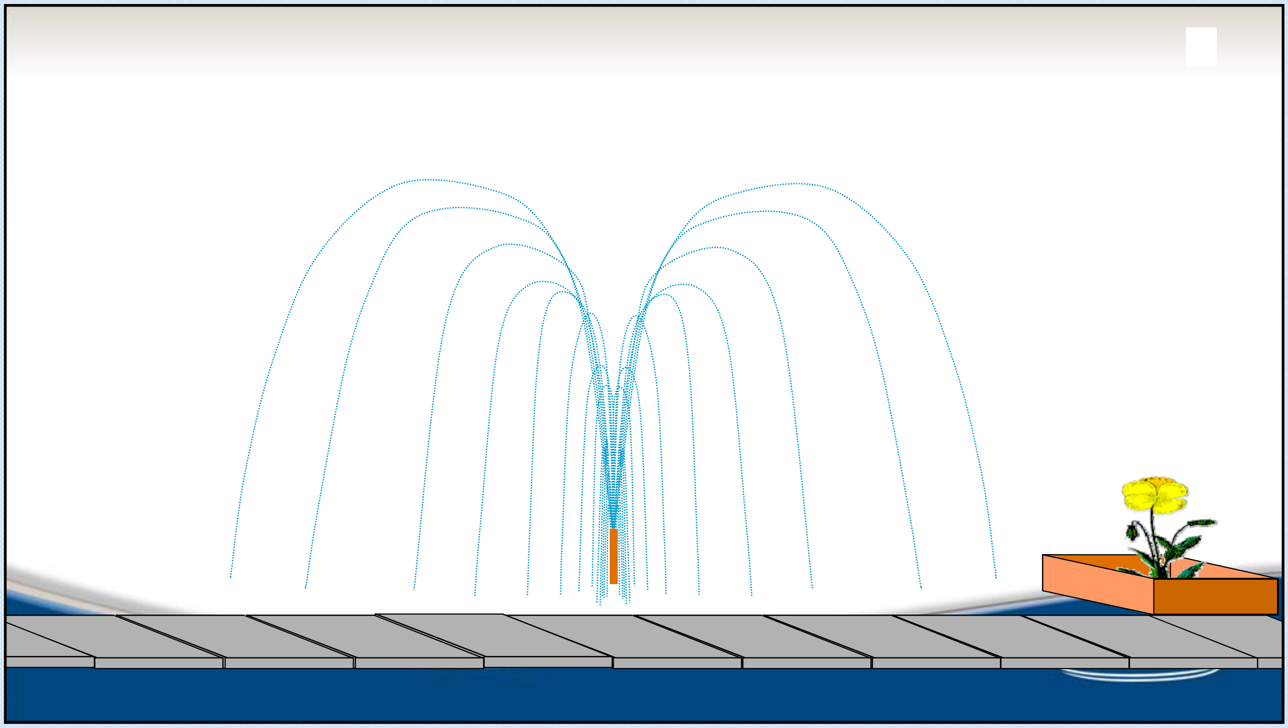
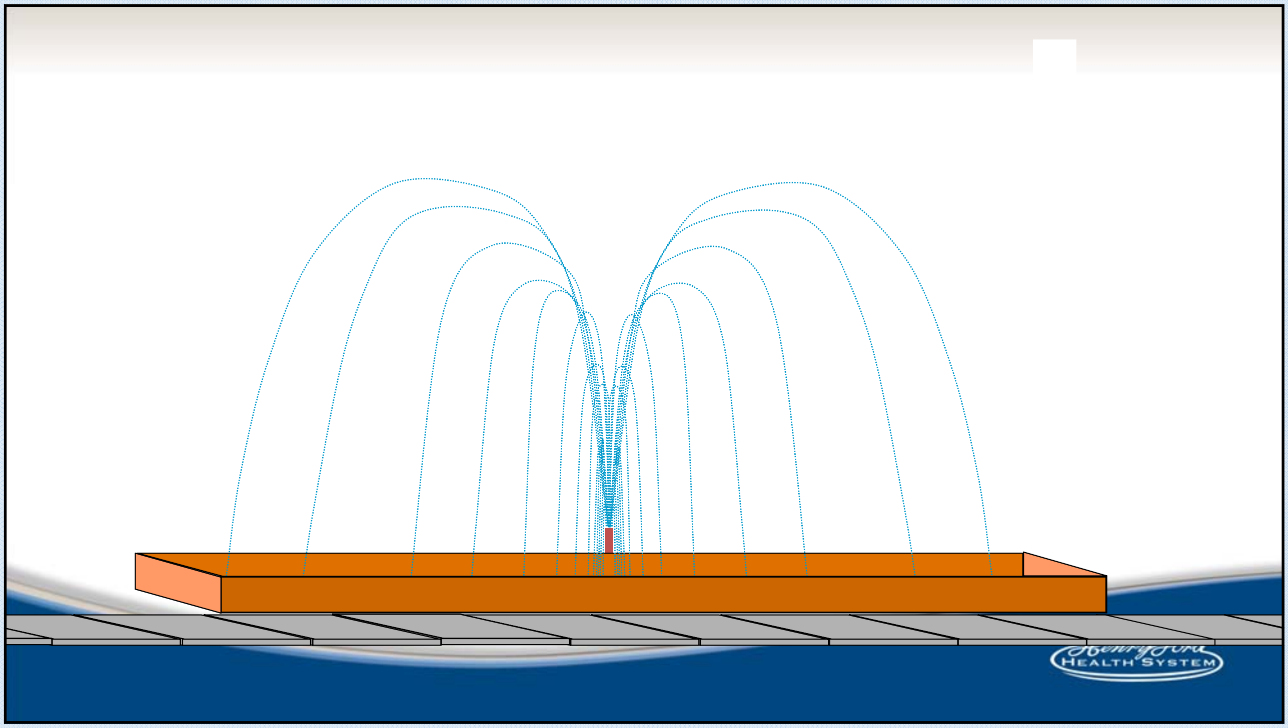
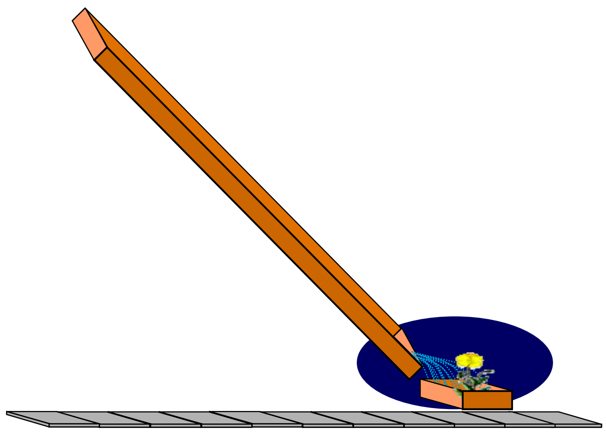
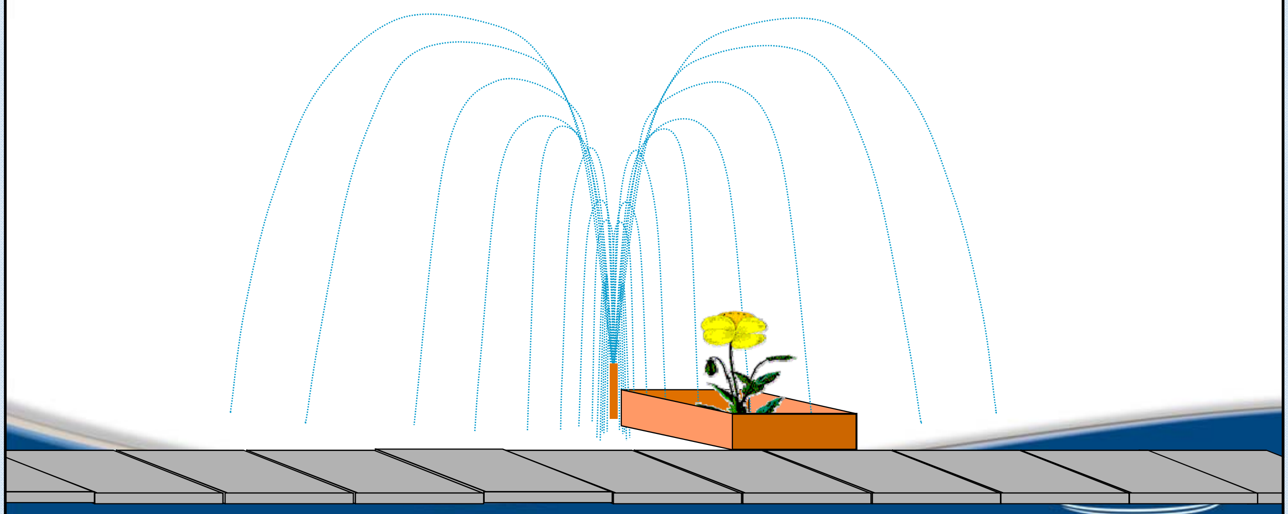
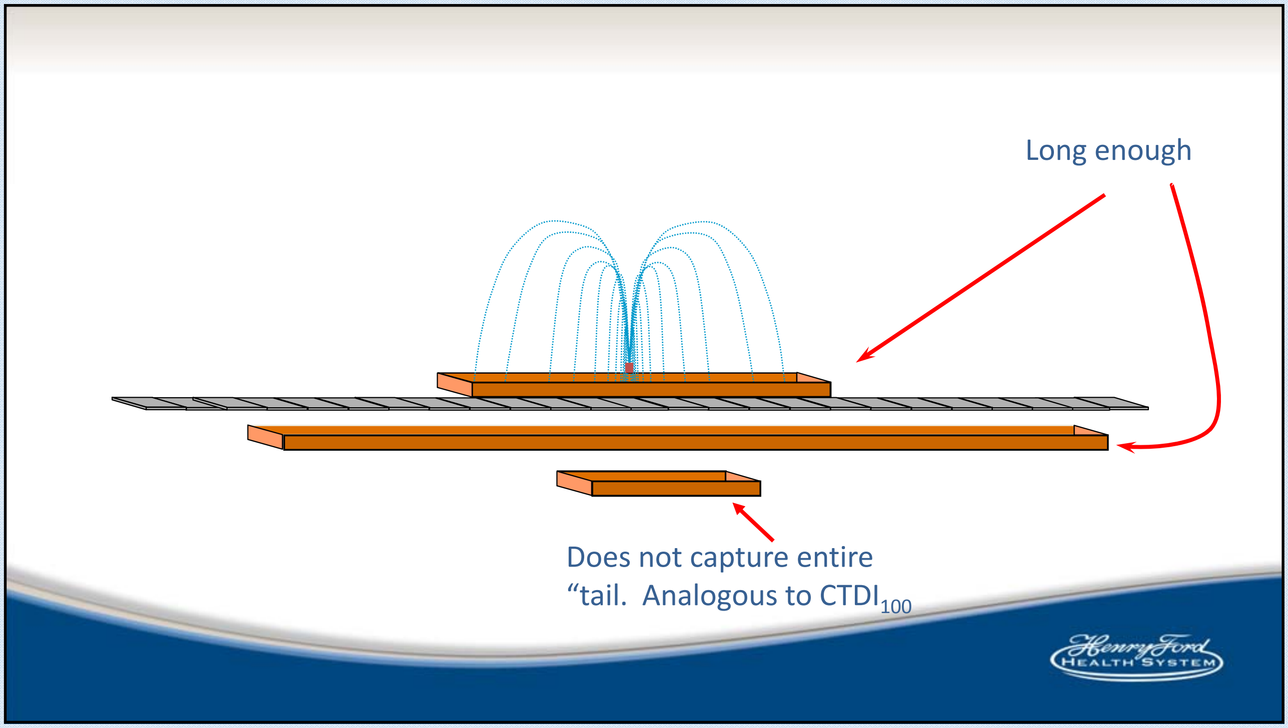



HEALTH SYSTEM



But if the path length is too short to capture all the water (analogous to $CTDI_{100}$)




Long enough
Does not capture entire
"tail. Analogous to CTDI100
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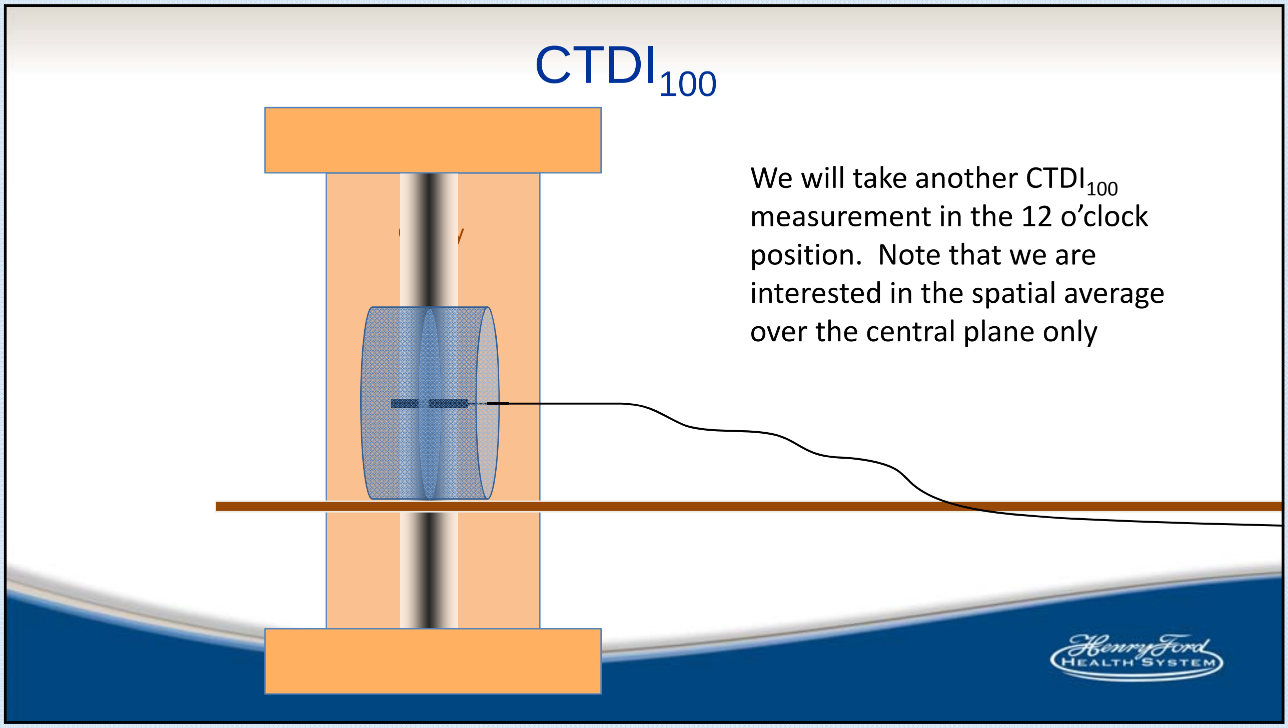
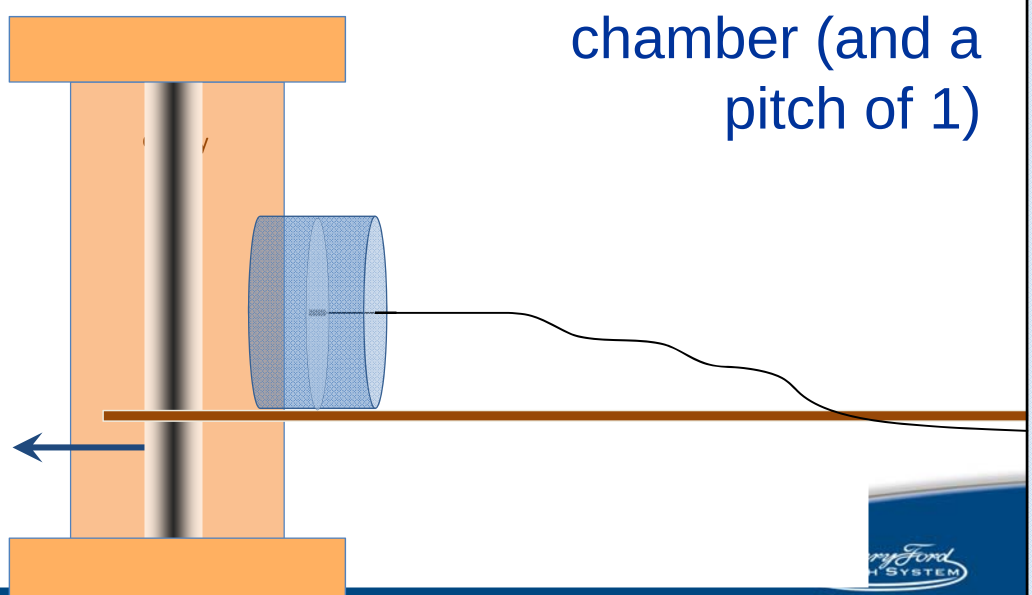

CTDI100
We will take another CTDI100 measurement in the 12 o'clock position. Note that we are interested in the spatial average over the central plane only
Henry Ford Health System

$CTDI_\infty$

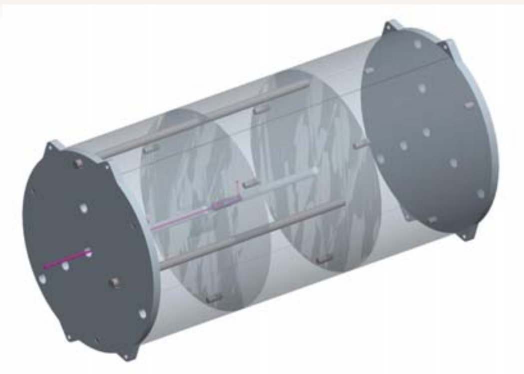
$$CTDI_\infty = fCE\frac{L}{nT}$$

- *C*omputed *T*omography *D*ose *I*ndex
- E: Measured exposure (mR) or air kerma (mGy)
- C: Calibration coefficient (~ 1)
- f : Converts units of exposure to air kerma (if necessary)
- L: Length of measurement chamber (where L is “long enough”)
- T: *z* axis width of a single row of acquired data (projected on axis of rotation)
- nT: *Detected* beam width: T × number of rows utilized n

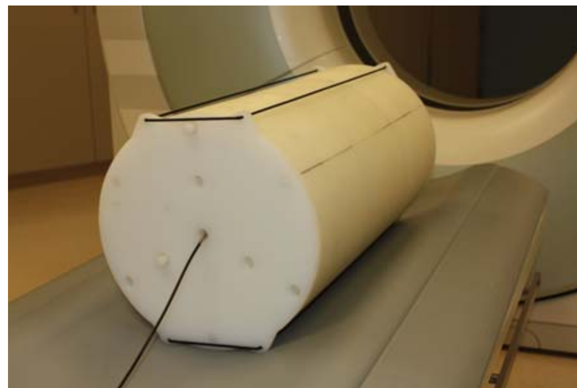
… is equivalent to a 100 mm scan with a small chamber (and a pitch of 1)



ICRU / AAPM (TG-200) Phantom

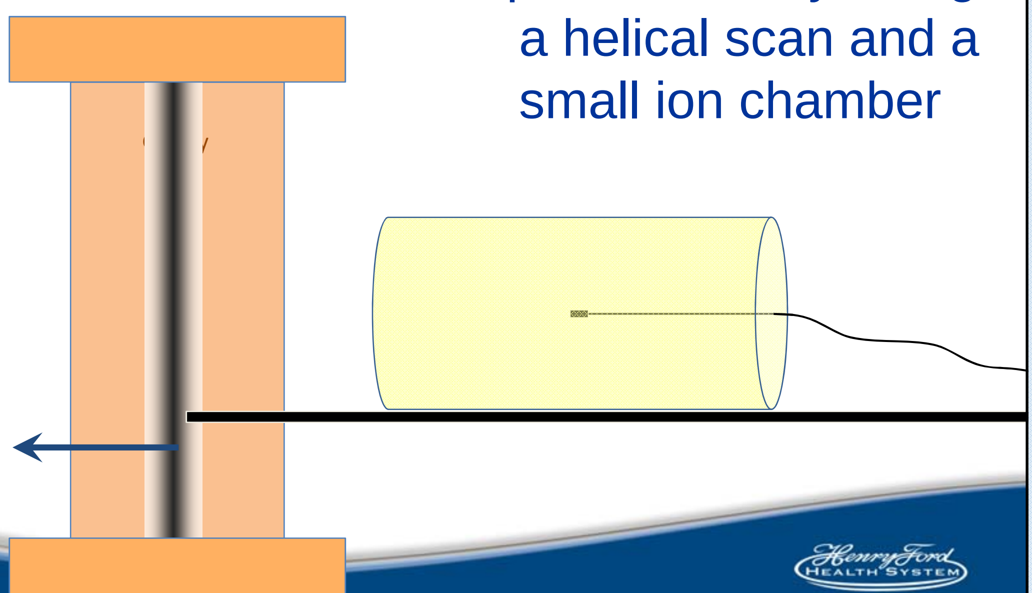


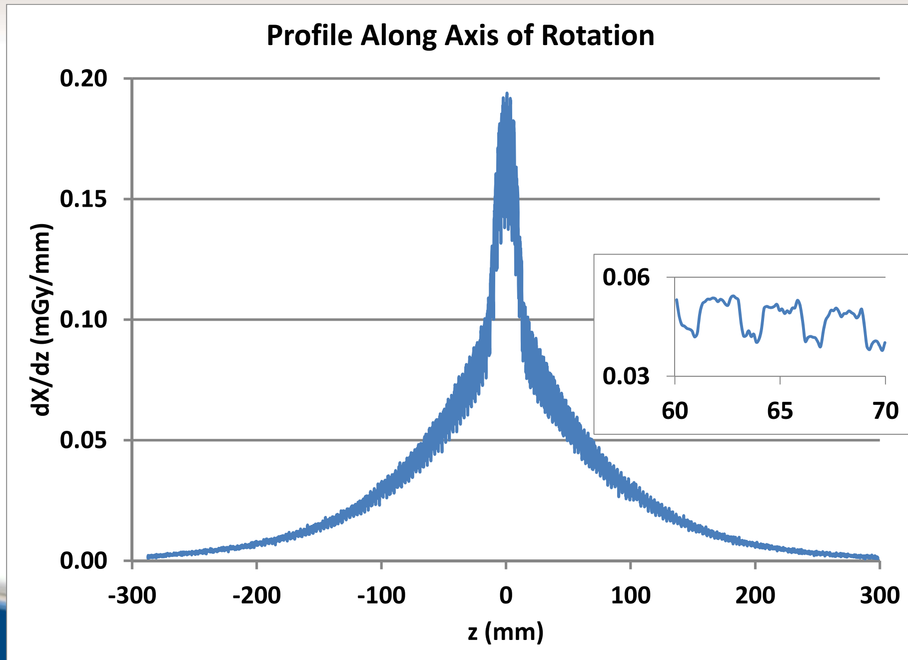
30 cm in diameter by 60 cm in length and is made of high density (0.97 g/cm^3) polyethylene. There are three sections, 29.3 lb (13.3 kg mass) each. (The 32 cm CTDI phantom has a mass of 14.4 kg.)



Designed and built by John Boone and George Burkett

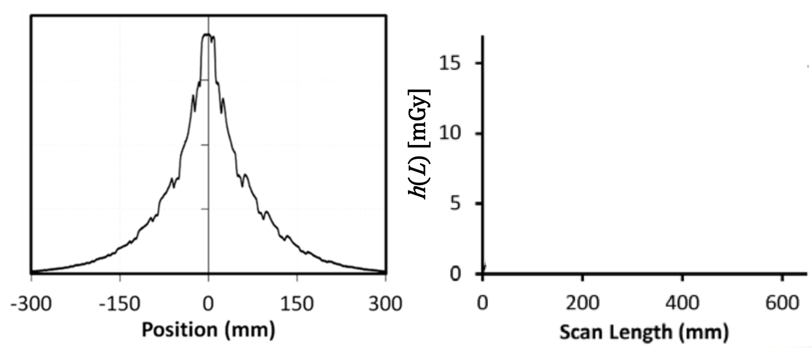
Capture the entire central axis profile directly using a helical scan and a small ion chamber





Using the dose profile to calculate *h*(*L*)

- Use the table speed, *dz/dt*, to convert time to distance.
- Assign the coordinate zero to the weighted average of the position
- Integrate outwards from zero. This gives us *h*(*L*).



Slide from Sarah McKenney

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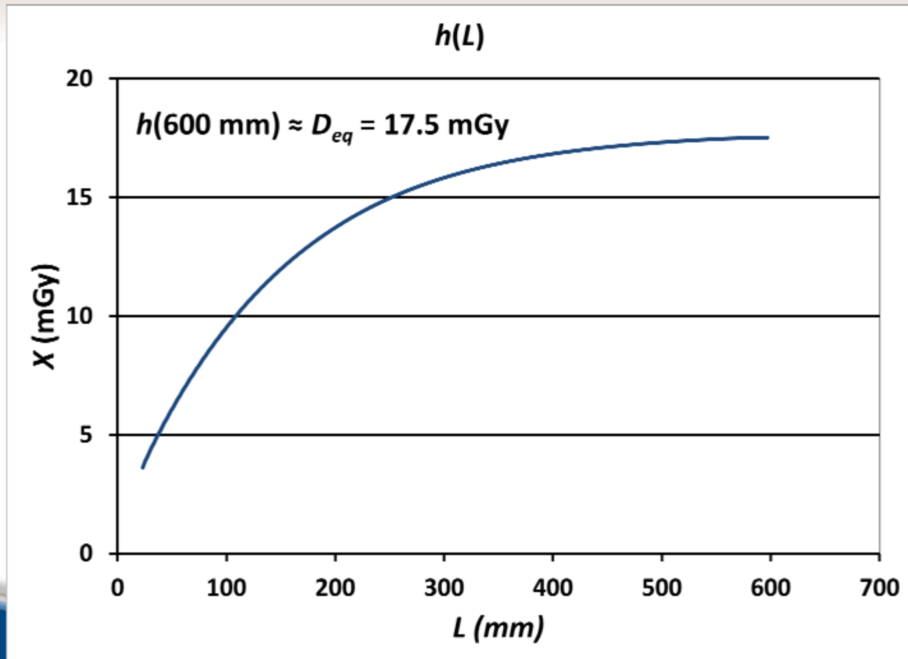
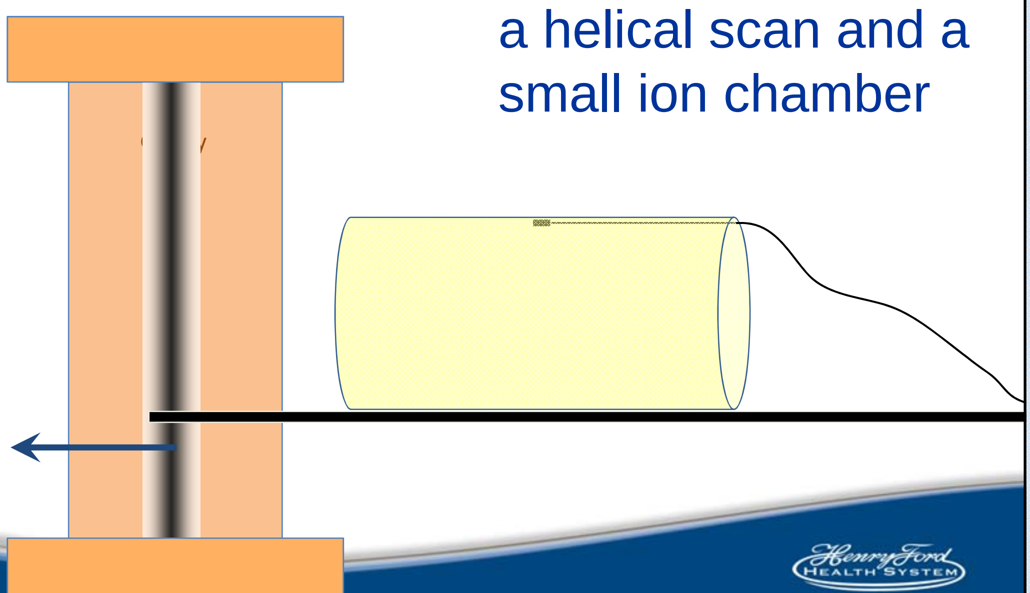
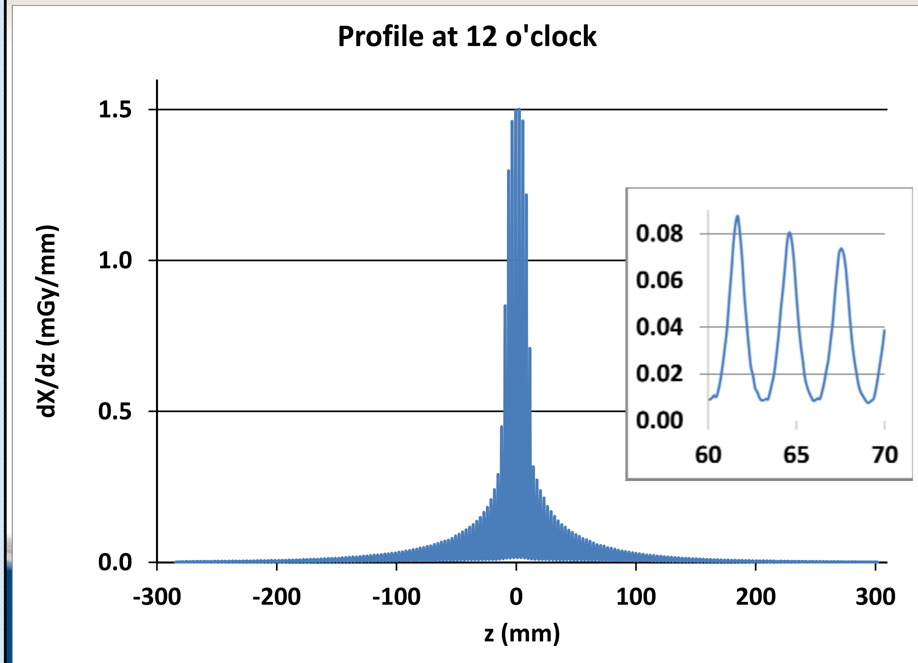


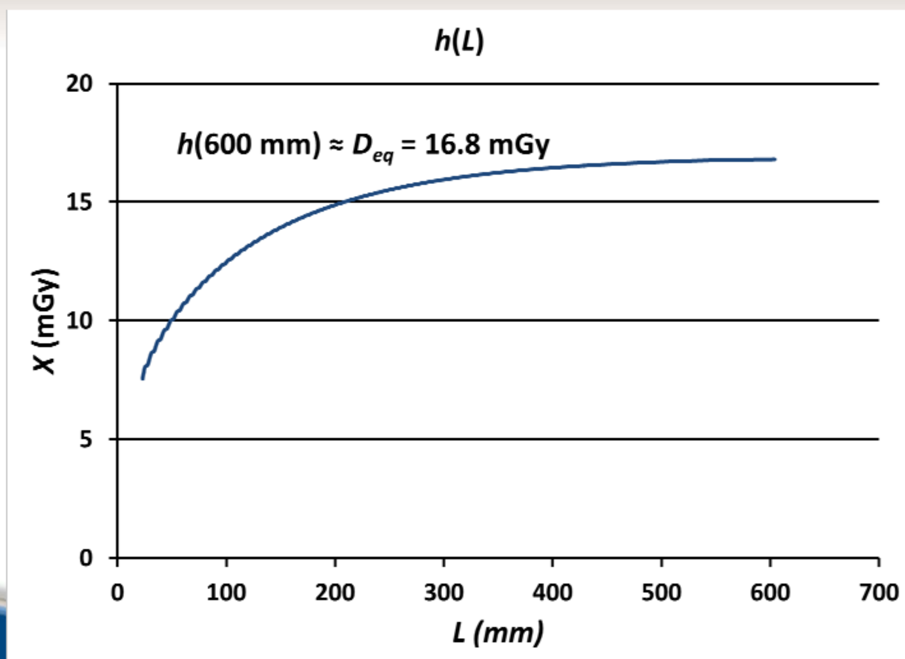
Capture the entire 12 o'clock profile directly using a helical scan and a small ion chamber





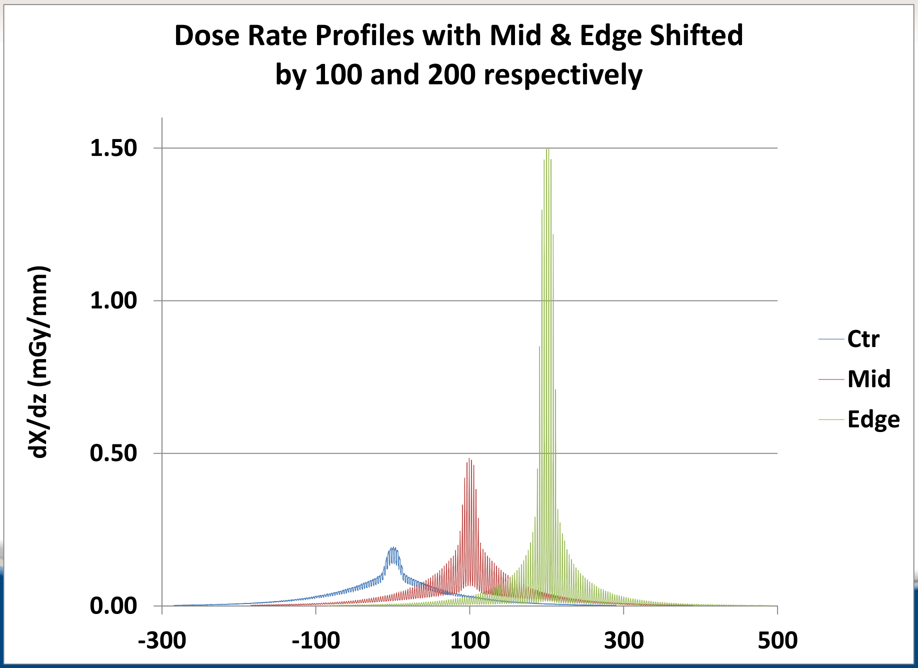
Narrow collimation and low pitch are preferable (for high spatial frequency bandwidth.

As the gantry rotates, the dosimeter moves in and out of the shadow of the phantom. Here the modulation approaches 100%

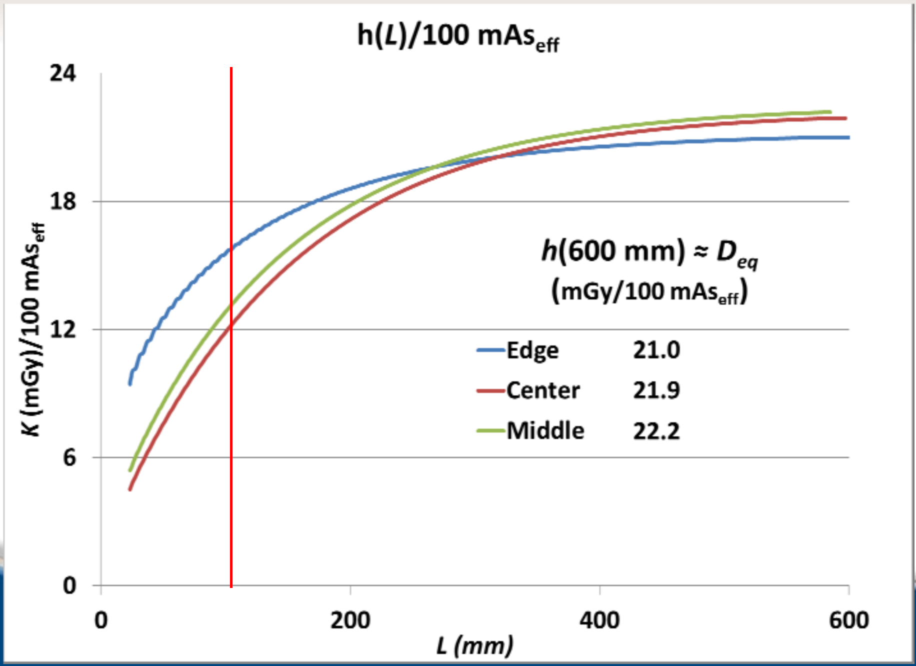


“Middle”

For completeness, there is also data at a radial distance of about half of the radius of the cylinder.



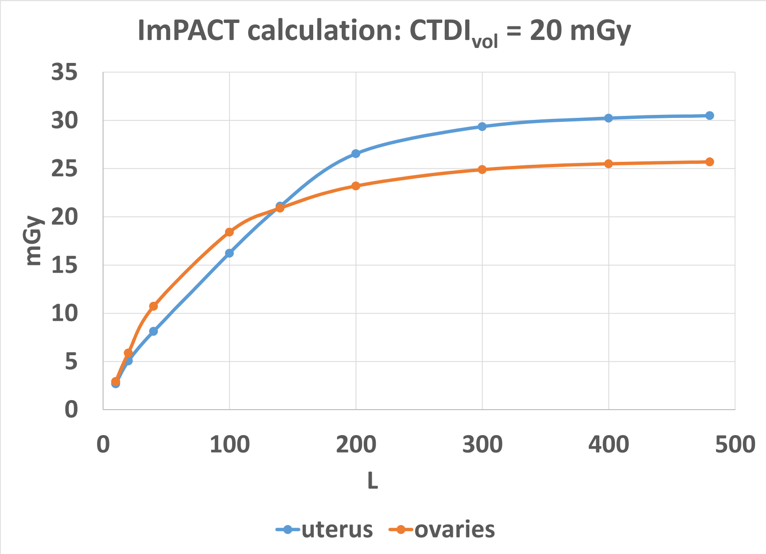
All three have approximately the same integral!

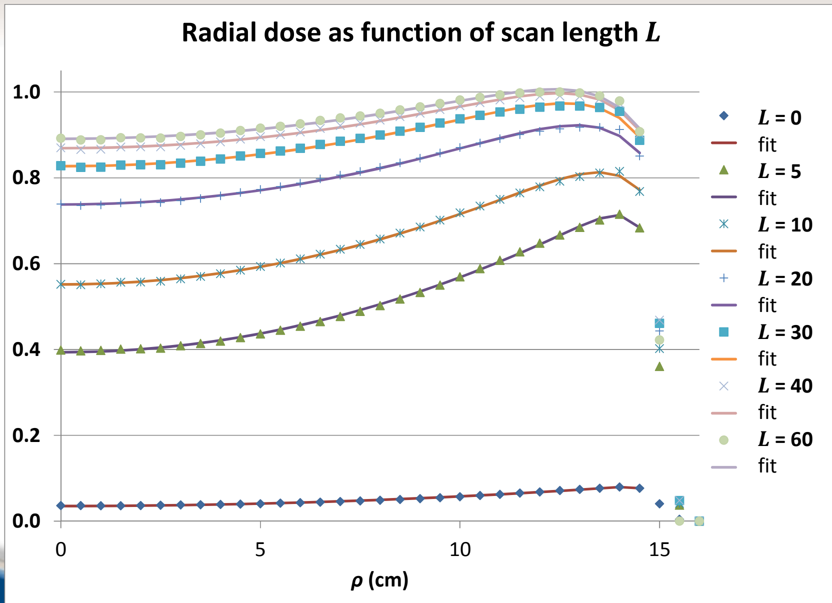


Note that the highest dose is between the center and edge (the "middle" position).

L = 100 mm corresponds roughly to $CTDI_{100}$.

How does this apply to anatomic models?





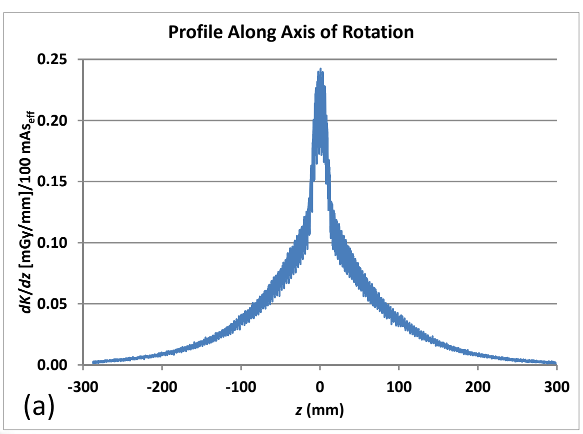
Gull-Wing Distribution

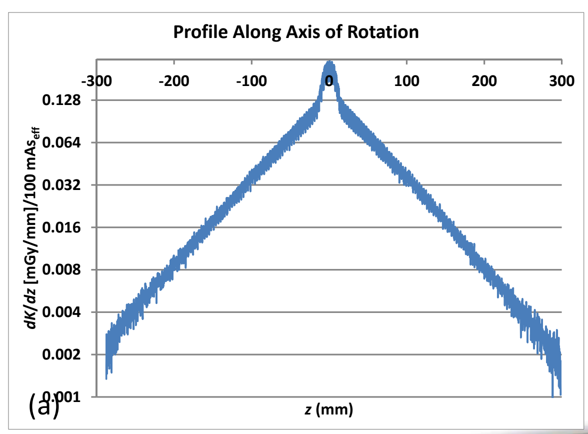
(based on Monte Carlo calculations by Wenzheng Feng)

$$D(\rho) = a_0 + a_2\rho^2 \\ -a_b\left[e^{-(R-\rho)/S} + e^{-(R-\rho)/S}\right]$$

Bakalyar, Feng, McKenney Med Phys 42, 3245 (2015); 43, 3640 (2016)

Finding D_{eq}: Log scale (base 2)



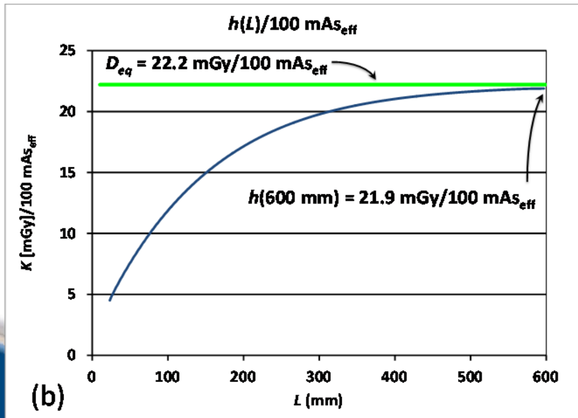


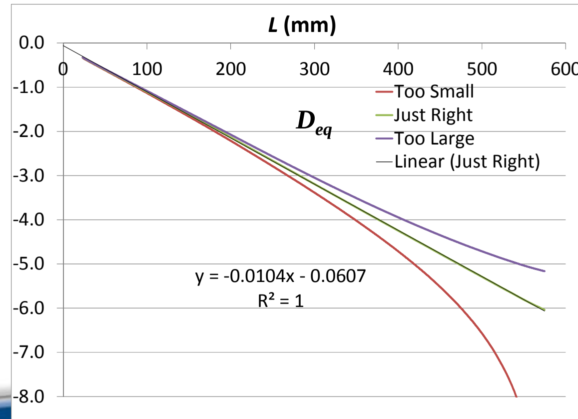
Rising capacitor eq: Adjust to get straight line on log plot

Rising Capacitor: $h(L) = D_{eq}\left[1 - \alpha 2^{-L/L_{½}}\right]$

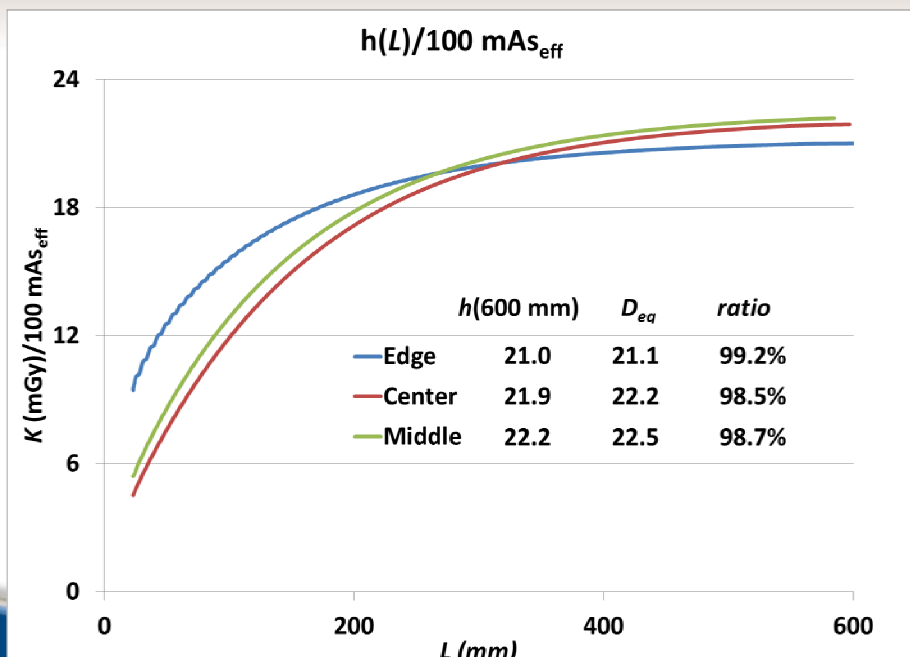
Define auxiliary equation: $g(L, D^*) \equiv log_2\left[1 - \frac{h(L)}{D^*}\right]$

If $D* = D_{eq}$ then
$g(L, D_{eq}) \equiv log_2\alpha - L/L_{½}$
then g will be a straight line on a log plot





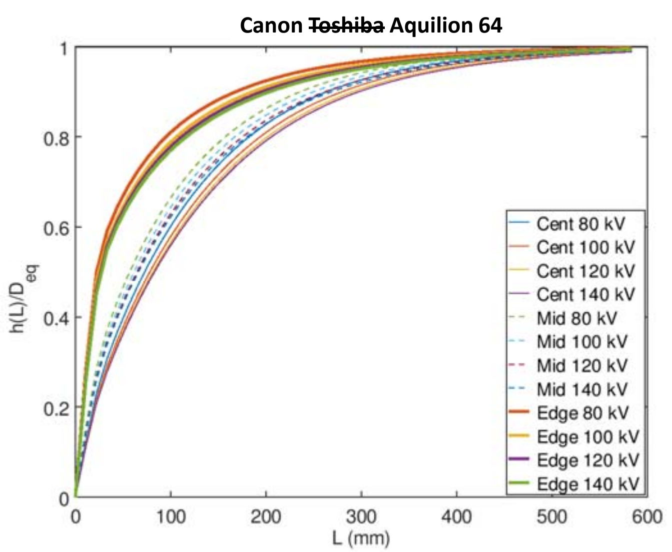
D. Bakalyar, Med Phys 43, 3395 (2016)



Look at $L_{1/2}$

Descrip-tion	h(600 mm) [mGy/100 mAs_{eff}]	D_{eq} [mGy/100 mAs_{eff}]	$1/L_{½}$ [mm^{-1}]	$log_2(\alpha)$	$L_{½}$ [mm]	α	$h(600)/D_{eq}$
Center (Philips)	21.89	22.21	0.0104	-0.0607	96.15	0.959	98.5%
Edge (Philips)	20.98	21.16	0.0105	-0.9550	95.24	0.516	99.2%
Inter-mediate (Philips)	22.18	22.47	0.0105	-0.1729	95.5	0.887	98.7%
Center (Siemens)	14.7	14.89	0.0103	-0.1130	96.90	0.925	98.7%

Tube potential and radius dependency for $H(L) = h(L)/D_{eq}$



All scanners showed the same trend. (Note that $H(L)$ is normalized for each scan; the table below shows how D_{eq} varies.)

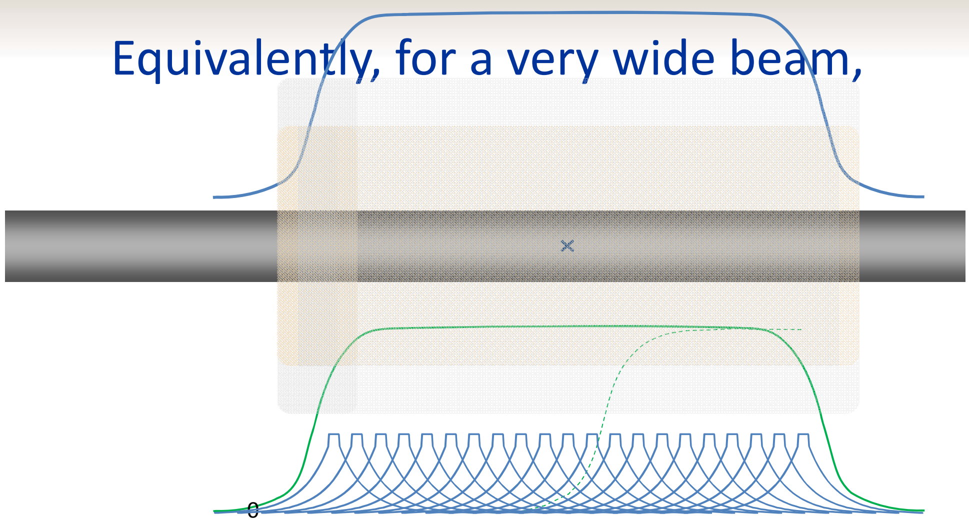
D_{eq}

	80 kV	100 kV	120 kV	135 kV
Center	7.35	13.82	13.04	14.29
Middle	8.10	14.76	13.70	14.94
Edge	7.90	13.82	12.54	13.58

Data analysis and plot from Joe Steiner

What about other geometries?

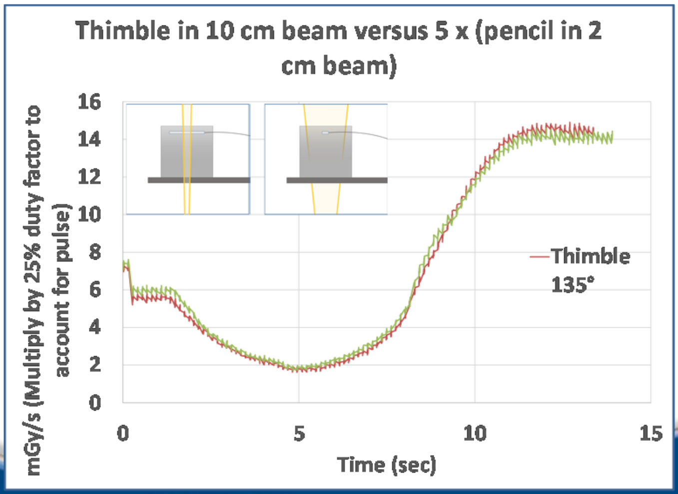
Equivalently, for a very wide beam,



we could imagine that we have a situation like the original example but with a coordinate change to a fixed table and a moving gantry. Then simply replace the series of narrow beams with a single wide beam and measure the dose at a single point in the center. (The curve has been smoothed.) The dose in the broad flat region is D_{eq}. Concept of Irradiated Length.

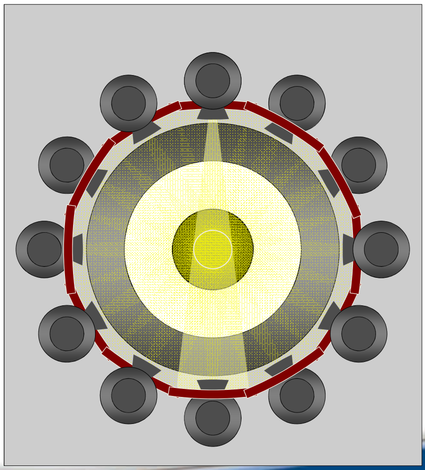
Dixon and Boone, Med Phys 37, 2703-2718 (2010)

Broad beam (C-arm cone beam) with small chamber versus narrow beam with pencil chamber



Bakalyar and Vanderhoek, Med Phys Vol 44, p2774 (2017)

What might be a problem for beams that do not subtend the phantom (e.g., C-arm cone beam CT)?

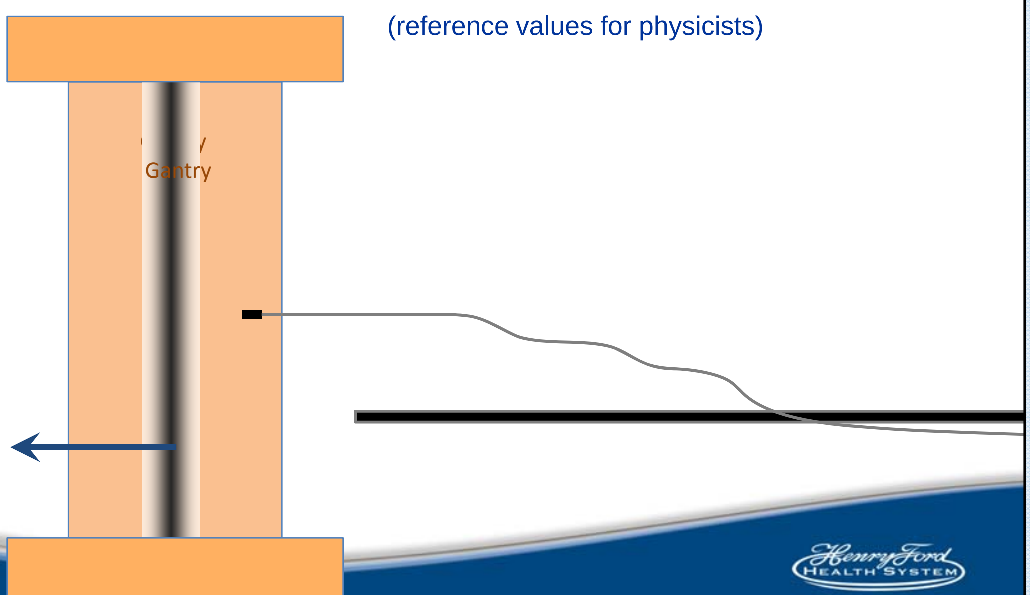


Measurements in air

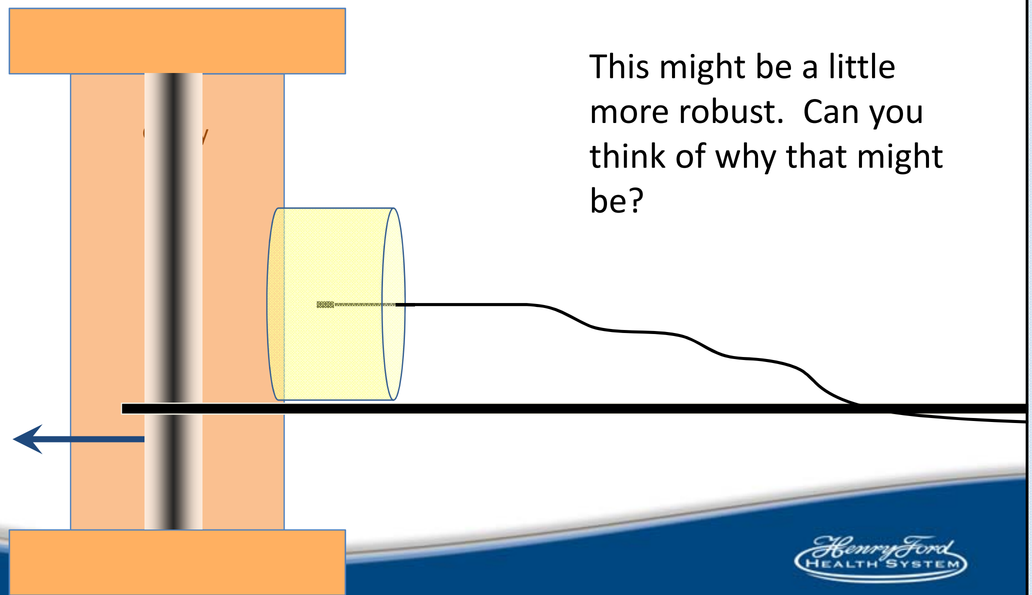
Thimble ionization chamber free-in-air and aligned along the axis of rotation. The chamber is attached to an extender rod from a lab stand, and the assembly is illuminated by the CT system alignment laser lights.

Measurements in air

(reference values for physicists)



Measurements in a single 20 cm long section



This might be a little more robust. Can you think of why that might be?

Thank you