

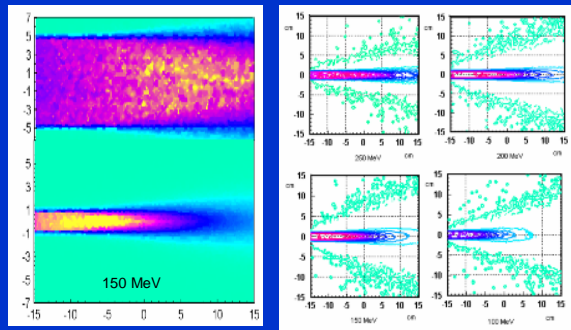
Very High Energy Electrons (VHEE) and 4D IMRT

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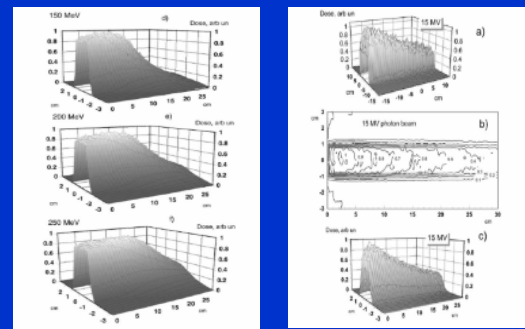
VHEE and 4D IMRT - Issues and perceptions

1. VHEE as a legitimate alternative to photon beam therapy.
2. Definite 4D IMRT in radiation therapy.
3. Obstacles in delivering true 4D IMRT with existing technology.
4. Fast scanning of pencil beam VHEE as a vehicle for 4D IMRT.

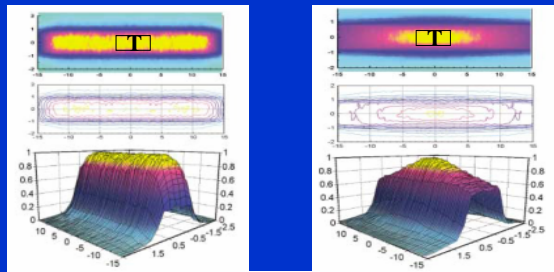
Dose for basic arrangement of VHEE beams – single broad and narrow beam



Comparison of dose from single beamlets - VHEE vs. photons

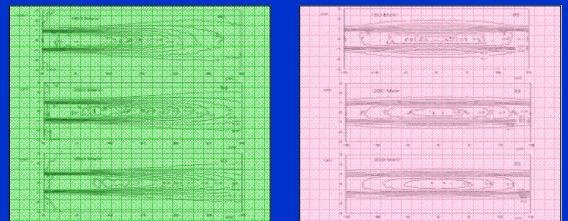


Comparison of ratio of target to integral dose from parallel opposed beamlets



Z (cm)	15 MeV photons	150 MeV electrons	250 MeV electrons
2	0.08	0.09	0.097
4	0.16	0.176	0.181
8	0.28	0.306	0.314
10	0.36	0.390	0.402

Comparison of penumbra for single and parallel opposed beams



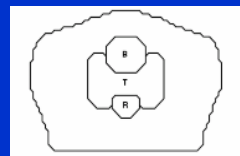
Penumbra (measured as the distance between 90% and 20% of dose maximum at a given depth) for single and parallel opposed electron and photon beams.

Depth (cm)	Penumbra (cm)			
	150 MeV	200 MeV	250 MeV	15 BEV
1	0.45	0.54	0.55	0.41
5	0.62	0.59	0.61	0.55
10	1.02	0.83	0.79	0.65
15	1.08	0.95	0.81	0.60

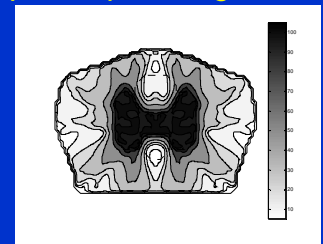
Message I

- Parameters (depth of beam penetration, penumbra, integral dose) of basic VHEE beam arrangements are adequate for dose distribution shaping for 3D conformal therapy and IMRT therapy.
- VHEE beam properties suggest advantage in their clinical utilization due to their better ratio of dose to target vs. integral dose.
- Potential shortcomings of VHEE (surface dose, photoneutrons).

Exploring potential advantage –case 1 VHEE multi-energy (50,100,150, 200, 250 MeV) optimal planning

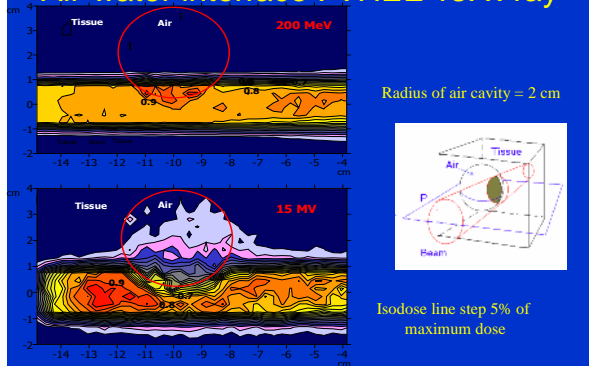


Prostate model case

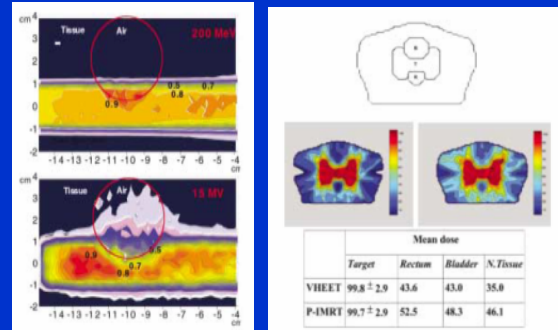


Optimal VHEE plan from nine coplanar beams

Exploring potential advantage –case 2 Air-water interface : VHEE vs. x-ray



Advantages of VHEE therapy vs. photon therapy



Message II

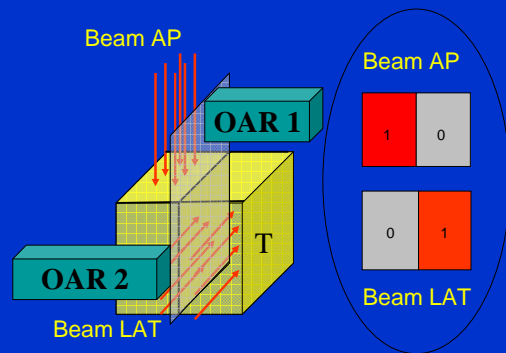
- VHEE provide potential advantages over photon therapy by avoidance of electronic disequilibrium and dose variation at tissue interfaces
- VHEE provide potential advantages over photon therapy due to their more favorable ratio of dose delivered to the target vs. integral dose delivered to the body
- VHEE can be particularly effective if whole spectrum of electron beam energies will be available for treatment and if VHEE therapy can be effectively integrated with photon beam therapy

Message III

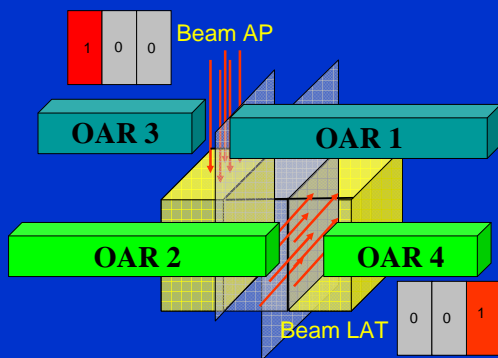
- VHEE based treatments avoid high dose at surface for multiple beam arrangements
- VHEE based treatments provide negligible dose equivalent enhancement from photoneutrons and induced radioactivity
- VHEE based treatments require shielding comparable to 50 MeV electron or photon treatments

VHEE advantage in 4D IMRT due to the feasibility of fast, electromagnetic scanning of VHEE pencil beams

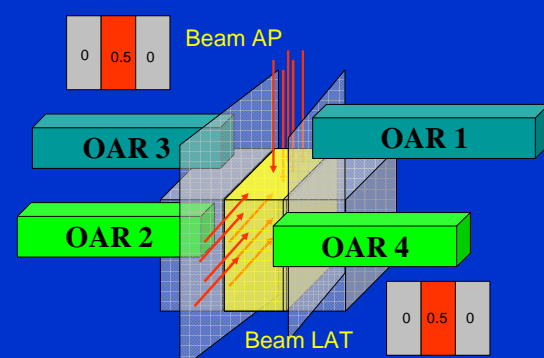
3D IMRT – principle (joint optimization for intensity maps over all beams)



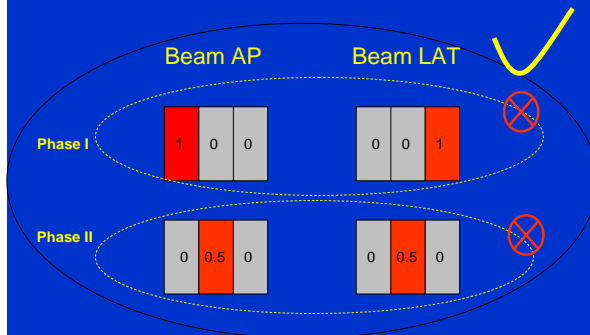
4D IMRT - moving organs (phase I)



4D IMRT – moving organs (phase 2)



4D IMRT – principle (joint optimization for intensity maps over all beams and phases)



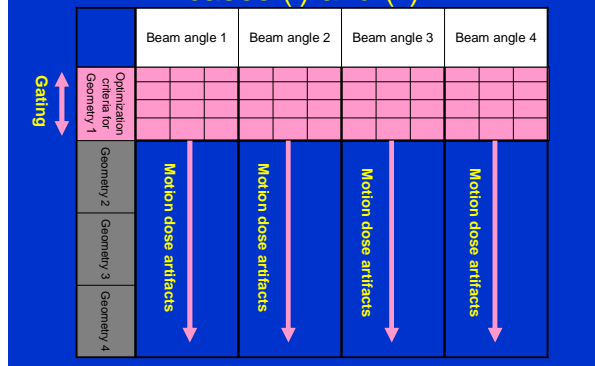
4D IMRT vs. 3D IMRT - I

- Best possible **3D plan** requires optimization that involves search for beamlet intensities that cover jointly **all beam directions**
- Best possible **4D plan** requires optimization that involves search for beamlet intensities that cover jointly **all beam directions** and **all body geometries**
- **No 3D plan for any stationary geometry can, under general conditions, achieve as favorable dose criteria as 4D plan optimized simultaneously for all body geometries**

4D IMRT vs. 3D IMRT – II

- Notice the similarity
 - The optimal plan for stationary body, as well as for moving body, requires evaluation of criteria for dose distribution accumulated over all time of body exposure
- Notice the difference
 - The delivery of optimal 4D plan requires proper redistribution of beamlet intensities over all geometries of the treated body – this is equivalent to realization of black and white “intensity” movie for each beam (TV therapy).
 - In contrast, the optimal 3D plan requires only proper accumulation of beamlet intensities for each beam over the entire interval of irradiation – this is equivalent to realization of black and white “intensity” (still) picture for each beam.

One phase planning (single 3D) – cases (i) and (ii)



Separate phase planning (multi 3D) – case (iii)

	Beam angle 1	Beam angle 2	Beam angle 3	Beam angle 4
Optimization criteria for Geometry 1				
Optimization criteria for Geometry 2				
Optimization criteria for Geometry 3				
Optimization criteria for Geometry 4				

Gating (vertical arrows on left and right)

Separate phase planning on 4D geometry (3.5 D) – case (iv)

	Beam angle 1	Beam angle 2	Beam angle 3	Beam angle 4
Geometry 1				
Geometry 2				
Geometry 3				
Geometry 4				

Optimization criteria for reference geometry (vertical arrow on left)

Gating (vertical arrows on right)

True 4D planning and delivery – case (v)

	Beam angle 1	Beam angle 2	Beam angle 3	Beam angle 4
Geometry 1				
Geometry 2				
Geometry 3				
Geometry 4				

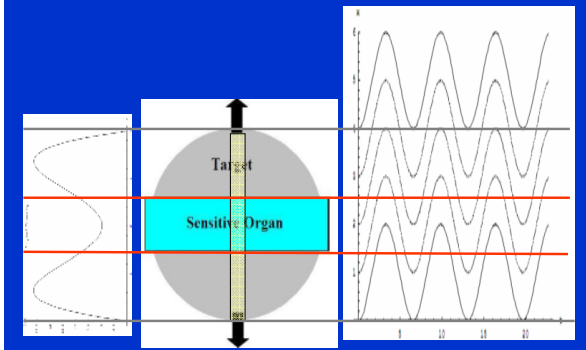
Optimization criteria for reference geometry (vertical arrow on left)

Fast scanning (vertical arrow on right)

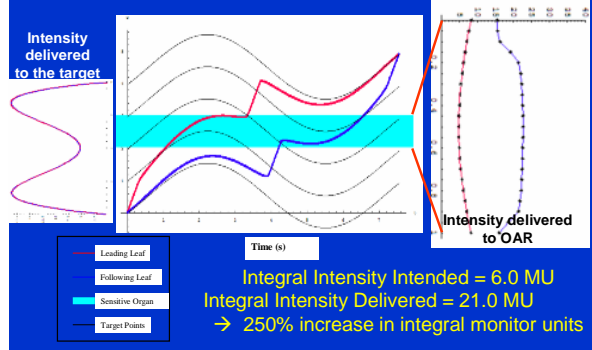
Towards 4D IMRT with DMLC delivery – what can be gained?

- Plan for single phase (3D)
- Target moving and OAR immobile
- DMLC delivery basic goal is to impose the planned intensity map over the target
- Non-uniqueness of the solution for DMLC to moving target allows to reduce the dose to OAR
- Passive solutions through DMLC motion correlation with phase of target shift
- Active solution with the modification of leaf velocities

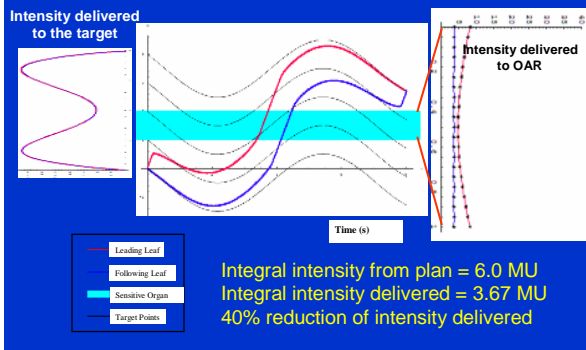
IMRT to moving target and stationary organ at risk (OAR)



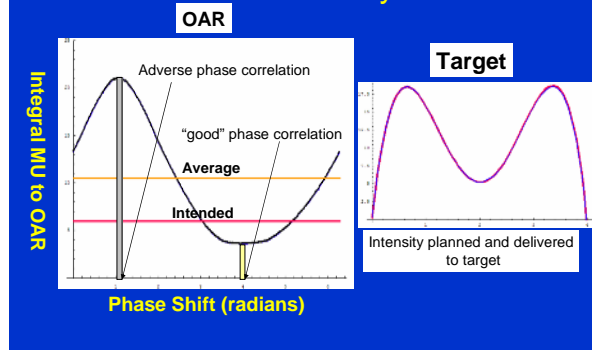
Increase of dose to OAR for adverse correlation of OAR and leaf motion



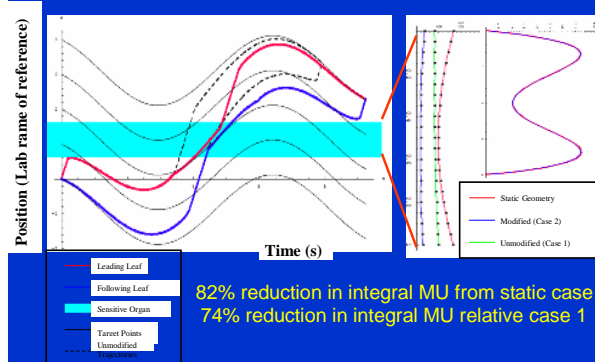
Reduction of dose to OAR for "good" correlation of OAR-leaf motions



DMLC IMRT for 4D therapy – statistical analysis



Partial 4D IMRT can provide generous reduction of dose to OAR



Conclusions

- VHEE therapy is a feasible alternative to photon and proton therapy (for some treatments VHEE is dosimetrically superior to photon therapy)
- True 4D IMRT treatment delivery is equivalent to creation of black and white movie displayed on the screen of each beam field
- VHEE electromagnetic scanning of electron pencil beam provides the physically viable tool for delivery of the true 4D IMRT

Acknowledgments

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