IMRT with Multileaf Collimators

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Plan of Presentation

- Definitions and examples of forward-planned IMRT
- Inverse treatment planning
- MLC and control system designs and effects on dose accuracy and delivery efficiency
- Clinical examples of inverse-planned IMRT vs 3DCRT
- Technical limitations of IMRT - including
  - Immobilization and positioning
  - Dose verification
  - Treatment parameter verification
  - Dose delivery errors

Intensity Modulated Radiotherapy (IMRT)

- Beam intensity is modified across each beam in complex way (excludes wedges, includes iterative few segment IMRT)
- Each beam treats only a portion of the target
- Can be planned by either standard "forward" or inverse iterative methods (though some would say inverse planning req'd to be called IMRT)
- Gives more degrees of freedom and potentially more conformal dose distributions than 3DCRT

Simple IMRT Methods using Forward-Planning

- Simple IMRT can be planned with conventional 3D planning programs:
  - Some fields consist of 2 or more subfields
  - Each subfield shape defined by conventional MLC
  - Relative intensity of subfields determined by iteration and implemented by varying MU per subfield
  - Planning goals can include
    - » improved dose uniformity
    - » concomitant boost
    - » normal tissue sparing

Simple IMRT Treatment Examples

- Examples of simple forward-planned IMRT treatments developed at UCSF include:
  - Boost treatments of Nasopharynx cancer
    - » 5 axial fields with 2 MLC subfields each
    - » 8 - 10 axial fields with wedging and clever beam angle choices to limit normal tissue dose and get uniform dose to target
  - Boost treatments to MRS-positive portion of prostate gland (Dominant Intraprostatic Lesion- "DIL")
    - » 7 axial field directions
    - » Simultaneously boost DIL to 90 Gy and remainder of prostate gland to 75.6 Gy

General IMRT Methods using Inverse-Planning

- General Methods of IMRT require the use of "inverse" treatment planning programs (UCSF experience totally with CORVUS system by NOMOS)
  - Begin with prescription of dose goals to target and normal tissues by physician
  - Planner defines number of beams, beam directions, delivery method and maximum acceptable complexity of intensity pattern
  - Program optimizes plan and returns with intensity pattern of each beam needed to approximate desired dose distribution

Treatment Planning Considerations for IMRT

- Conventional "forward" planning leads to increase in number of fields compared to 3DCRT
  - Can increase treatment time
  - Optimization may require many iterations
- "Inverse" planning programs with computer optimization generally required for IMRT
  - Require complete change in thought processes
  - Verification more time-consuming
  - Results non-intuitive
  - Optimization can be impossible if prescription unrealistic
  - Effects of prescription change difficult to predict

Inverse Treatment Planning

- CORVUS treatment planning system (NOMOS) used by many groups
- Prescription page requires dose goals for target and normal tissues input as 3-point DVHs
- Planner chooses beams and no. of intensity levels
- Opportunity to place margins between CTV and PTV
- Objective function minimized using simulated annealing with penalties based on clinical input
- Output is discrete intensity profiles for each defined beam direction and MLC segments and weights for accelerator of choice

Inverse Treatment Planning

- Other inverse planning systems now becoming available - MSKCC, Helios, Helax, Pinnacle, CMS, KonRad, etc.
- Some of these produce smoothly varying intensity patterns as output and others with discrete patterns
- Comparisons of IMRT delivery systems must use plans generated for specific type of delivery (DMLC, SMLC, IMAT, tomotherapy)

Commercial IMRT Delivery Methods Using Multi-Leaf Collimators

- IMRT delivery methods used to date include:
  - Static MLC IMRT with fixed gantry angle (step and shoot technique)

    MLC leaves are kept stationary when the beam is on
  - Dynamic MLC IMRT with fixed gantry angle (sliding window /step and shoot techniques)

    MLC leaves can move when the beam is on
  - Sequential Tomotherapy (MIMiC)

    Both MLC leaves and gantry are moving when the beam is on

Static MLC vs Dynamic MLC

- Static MLC

  Leaves cannot be moved when the beam is on. Leaf motion and the radiation are executed sequentially.
- Dynamic MLC

  Leaves can be moved when the beam is on

  Leaf motion and the radiation are separately controlled and can be executed simultaneously

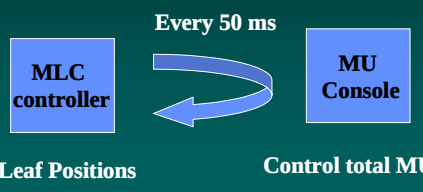
"Step and Shoot" SMLC-IMRT

- Advantages of this method of IMRT:
  - Portal verification of intensity pattern feasible
  - Easy to understand clinically
  - Easy to resume interrupted treatment
  - Relatively simple accelerator control system needed
  - Both forward and inverse planning possible
- Disadvantages of this method:
  - Complex problems require lots of segments
  - Dosimetry of small fields, small MU in question
  - Time required for treatment can be significant, depending on level of plan complexity and speed of control system

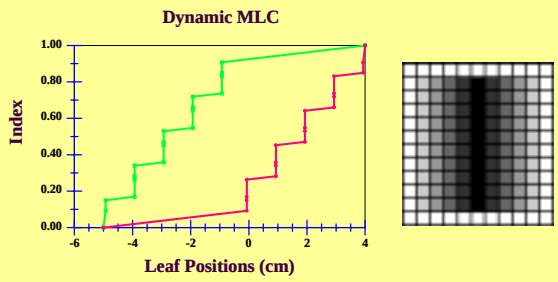
Step and Shoot vs. Sliding Window for DMLC

- The leaf positions and the cumulative MU are correlated:

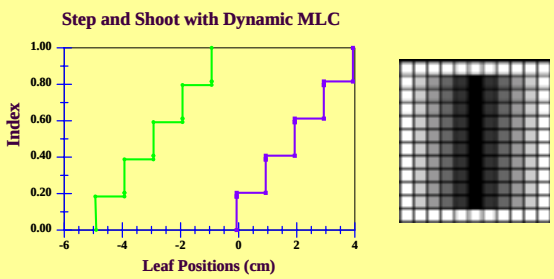
$$MU_T = \Sigma (\Delta M_i , X_i)$$



Sliding window For DMLC



Step and Shoot For DMLC



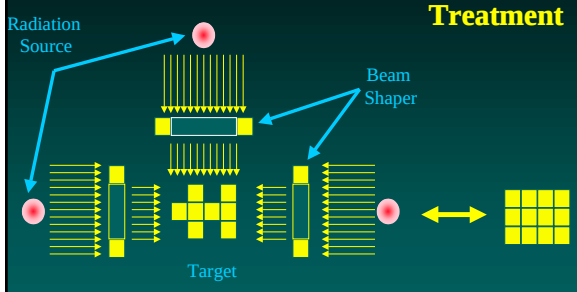
DMLC IMRT

- Can efficiently deliver highly modulated field
- Artifacts may occurs when small MUs and high dose rates are delivered.
- Requires relatively more MUs compared with static delivery

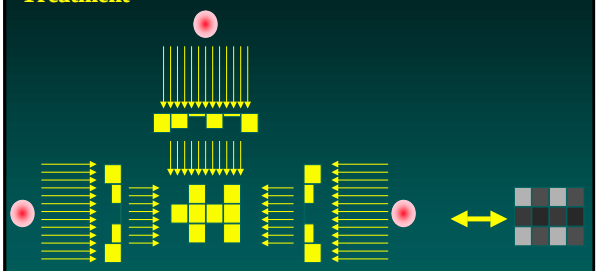
IMRT Delivery Methods Using Special MLC

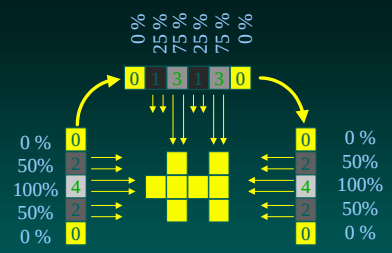
- Thousands of patients treated to date with Peacock MIMiC collimator (NOMOS Corp.) attached to the head of a conventional linac (80 at UCSF)
  - Collimator has 40 tungsten leaves which are pneumatically driven in and out while gantry rotates
  - Treatment area for each arc is 2 x 1 cm or 2 x 2 cm along body axis and up to 20 cm in width
  - Each leaf defines a relative beam intensity of from 0 % up to 100 %, generally in 10% steps, for each 5 deg. of arc rotation
  - Typical arc length is 270 degs. which gives dose distribution equivalent to 55 evenly spaced beams with 10 levels of intensity

Conventional Treatment



IMRT Treatment





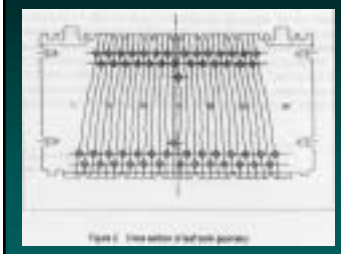
As the gantry rotates, each leaf stays open for a percentage of every 5 degrees of rotation proportional to its relative intensity

Multileaf Collimator Designs

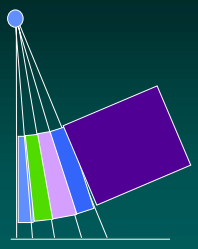
- Each manufacturer has a different design for their MLC
  - Location, leaf width, and leaf end design
  - Single focused or double focused
  - Restrictions on motion (path, over-travel, interleaf)
  - Field size
- These factors have an impact on dose delivery and must be considered in treatment planning

Single Focused and Double Focused MLC

SOURCE

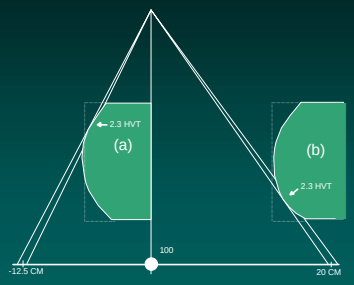


Focused in Y

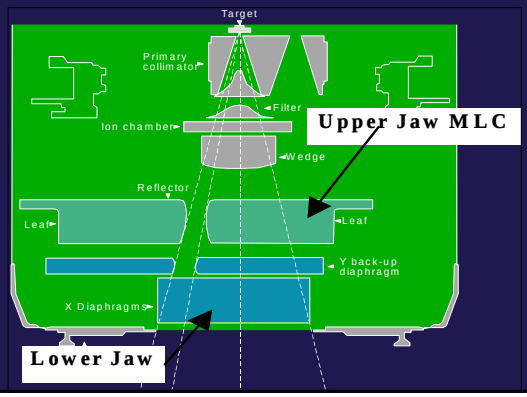


Focused in X

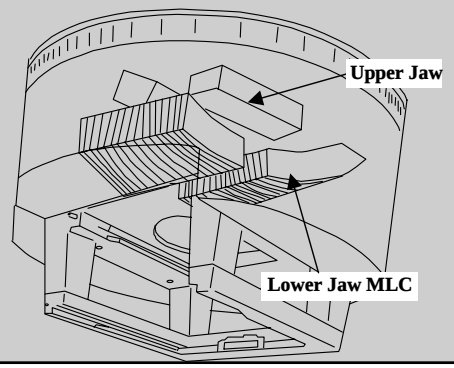
Rounded Leaf End vs Penumbra



Elekta MLC System

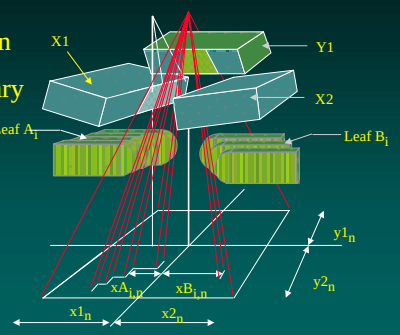


Siemens MLC

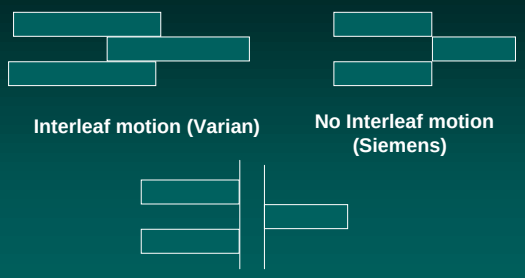


Varian MLC System

Varian Tertiary MLC



Leaf Motion Constraints



Interleaf motion (Varian)

No Interleaf motion (Siemens)

Minimum Gap (Elekta)

MLC Field Size for IMRT

Linac	IMRT Field Size	Nominal Field Size
Varian	30 x 26 (40) cm^2 (2 x 14.5 cm)	40 x 26 (40) cm^2
Siemens	21 x 20 (27) cm^2	40 x 27 (40) cm^2
Elekta	25 x 25 cm^2	40 x 40 cm^2

Siemens IMRT Delivery System

- Automatic field sequencing system (Primeview/SIMTEC)
  - » For both conventional and IMRT delivery
  - » Automatically deliver all gantry angles including segments in each IM field
  - » Supports step and shoot SMLC delivery
  - » ~ 5 - 6 sec. R/V overhead per segment
  - » Treat 100 - 120 segments in 20 minutes
  - » Only integer MU can be specified per segment
  - » Supports Network RTP

Overcoming Jaw Overtravel Limits with the Siemens MLC

- Conventional field size = 27 x 40 cm^2
- MLC size = 27 x 21 cm^2
- Normally use 21 x 20 cm^2 because jaw over-travel distance limited to 10 cm. and jaw is required to back up MLC pattern to within ~ 2 mm
- Limitations have clinical significance

Results: Random Pattern

	Standard Algorithm	Std. + IR	Alt. Direction	Alt. Dir + IR	Intensity reduction + opening limits
Segments	36.6±1.3	36.8±2.2	36.2±1.4	36.2±1.7	36.2±1.7
# success	837	991	849	990	968
# fail	163	9	151	104	32
% success	83.7	99.1	84.9	99.0	96.8

Combine Features

- Not all patterns are equal
  - What works for one intensity plan may not work for another
  - Try intensity reduction first
  - Add opening limits
  - Try different directions
  - Try different combinations of IR and OL
- Results show virtually 100% of all clinical and random patterns can be treated successfully

Conclusions of Studies with Siemens MLC-IMRT System

- Field length limitation can almost always be solved by re-segmenting intensity pattern (full 27 cm length adequate for almost all cases) (need control over segmentation process)
- Field width limitation can be solved by appropriate choice of beam angles in most cases
- Higher delivery speed and higher leaf setting accuracy would be useful

Varian IMRT Delivery System

- Current version of VARIS
  - » Supports dynamic sliding window and step and shoot IMRT delivery
  - » No R&V overhead time for each segment
  - » MLC controller and MU console are separated
  - » ~ 1.2 minutes/field
  - » Fractional MU per segment supported
  - » Network RTP

Varian DMLC Studies

- Errors in intensity patterns have been noted when overlaid on port films at typical port film doses of ~ 8 MU
- This launched an investigation of delivered dose distributions at various doses and dose rates for complex IMRT fields
- Studies were performed with film and with ion chambers placed at both high and low dose regions in phantom treated with clinical plans recalculated for phantom geometry

Step and Shoot Delivery using DMLC control system

Every 50 ms

Controls leaf positions

Controls total MU

Communication delay between segments creates unavoidable dose errors

Dose Errors due to Communication Delay

The dose error in each segment:

$$\Delta = RT/M$$

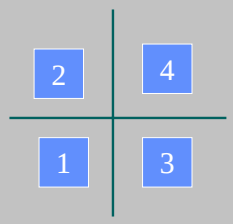
(R: dose rate, T: time delay, M:MU/segment)

e.g. R = 400 MU/min, T=50 ms, M=1 MU/seg

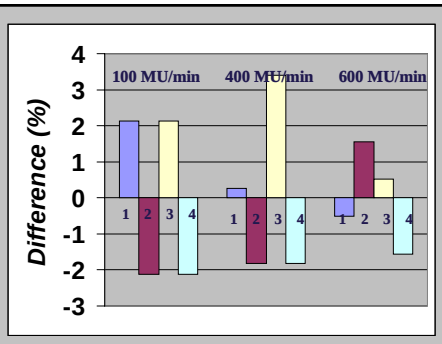
$$\Delta = 400/60 * 0.05 = 0.33$$

Δ can be significant especially if R is large and M small

Experiment

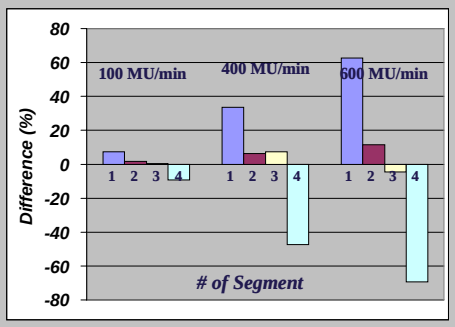


0.25 MU/seg
1.0 MU/seg
4.0 MU/seg
16.0 MU/seg
20.0 MU/seg
at
100 MU/min
400 MU/min
600 MU/min



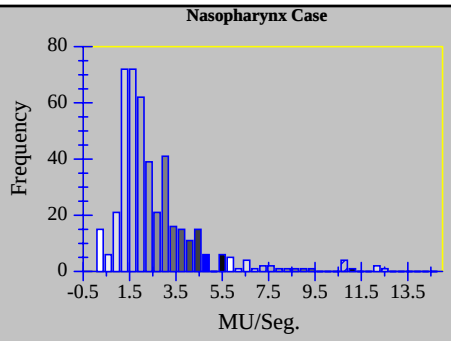
1 MU/seg delivered as separate fields (SMLC-IMRT) similar to Siemens control system

(Deliverd on Varian CL2300, 6MV, 100 SSD, 1.5 cm depth)



1 MU /seg delivered with DMLC control system in dynamic step and shoot mode

(Cl2300, 6MV, 100 SSD, 1.5 cm depth)



Rx technique: 15 gantry angles, 10 intensity levels, total # of segments = 491, dose rate = 400 MU/min - note that only 30/491 (<6%) segments are first or last

Dosimetric Verification- Results

- Observations <u>dependent</u> on delivery system
  - Observable errors in intensity pattern only seen with Varian DMLC dynamic step and shoot system at port film doses (~8 MU) - no observable errors for typical clinical doses of > 90 MU per field
- Observations <u>independent</u> of delivery system
  - High dose regions of plan (typically >85% max) were generally within 2% of calculated
  - Lower dose regions (typically planned for 30 - 50 % of max) were 10 - 15 % higher than planned
  - In general, higher complexity (more intensity levels and segments) gave higher discrepancies

Dosimetric Verification - Interpretation

- Dose discrepancies approximately the same for plans delivered with Siemens and Varian accelerators - i.e., independent of dose delivery system
- Probable cause is dose calculation algorithm within CORVUS planning system which does not deal well with small fields and leaf transmission and scatter - soon Peregrine can answer question
- Dose errors due to DMLC control delays probably not clinically significant though more research needed

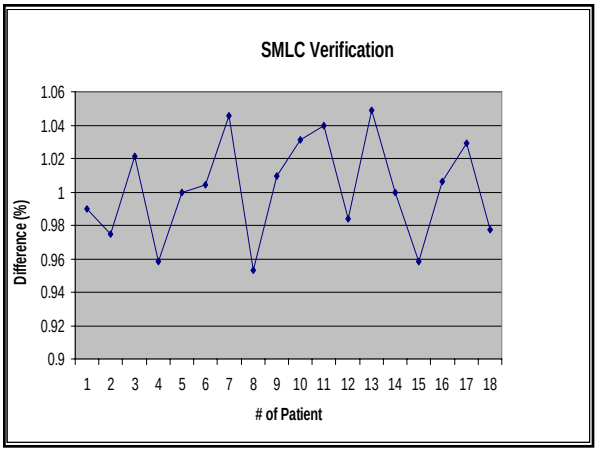
Treatment Planning Guidelines

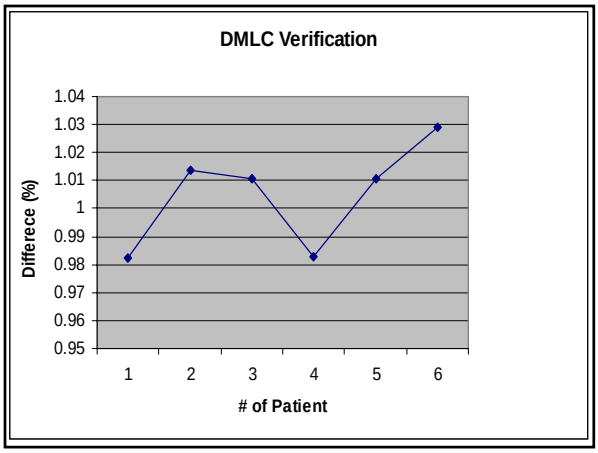
- Until dosimetry totally understood, the safe approach is to minimize IMRT plan complexity (and, presumably dose delivery errors) :
  - For SMLC, minimize plan complexity to reduce delivery time and dose errors and minimize effect of integer MU
  - For step and shoot IMRT with DMLC, avoid highest dose rate and minimize plan complexity to reduce dose errors
  - For both delivery methods, complexity can be reduced by hand-selecting beam directions and using fewer numbers of intensity levels (e.g., 5)

Dosimetric Verification Procedures at UCSF

* In the beginning of IMRT treatments at UCSF, dosimetric verification was performed prior to each patient's first treatment using solid water phantom and ion chambers for absolute point doses check and film for relative dose distribution check.

* Results - The measured point doses near the maximum for more than 40 plans generated with Corvus (version 2.0 and later) were all within 5% of predicted doses. Therefore, patient specific dosimetry no longer done routinely at UCSF.



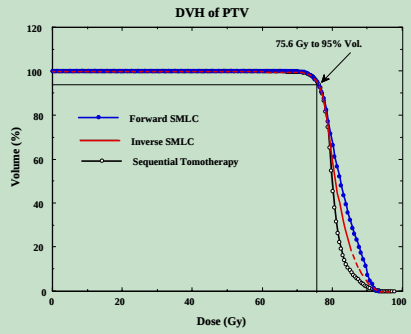


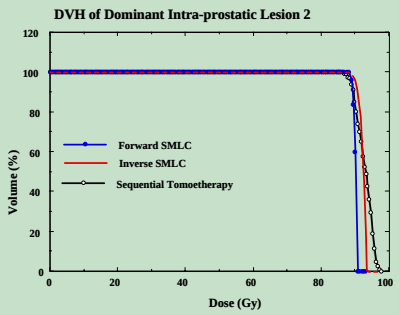
What have we learned so far with our IMRT experience?

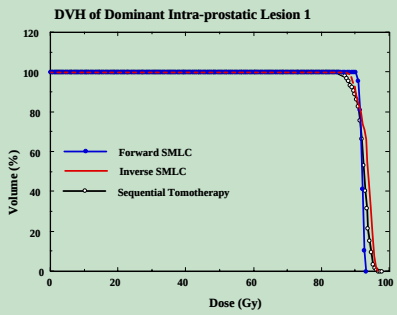
- Clinical needs drive us to complex IMRT plans (many fields and segments) therefore, delivery speed is important
- Dose accuracy not as good for high complexity due to large numbers of small fields and small dose per segment
- IMRT field length and field width requirements can limit use

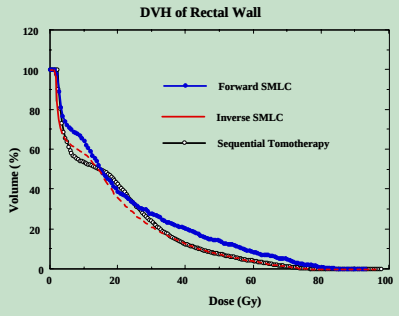
Clinical Comparisons - I

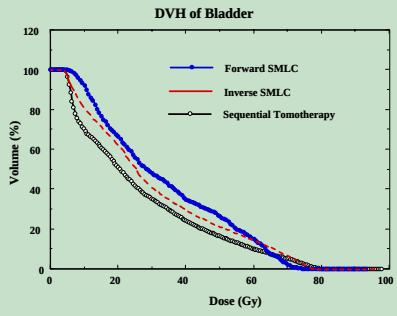
- Prostate carcinoma
  - MRS-identified lesion (DIL) within prostate
  - Goal to deliver 90 Gy to DIL
  - Goal of 75.6 Gy to body of prostate
  - Rectal and bladder doses below tolerance
- Treatment plan comparison
  - Forward-planned 7-Fld, 18-20 segments
  - Inverse-planned Peacock MIMiC plan (ST)
  - Inverse-planned 7-Fld, 10 intensity level MLC-IMRT plan











RESULTS

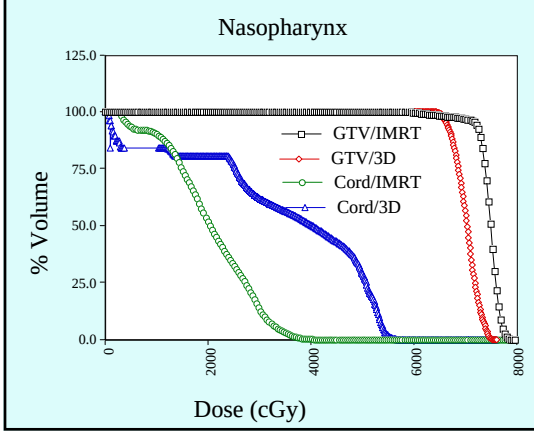
Endpoint doses to rectal wall

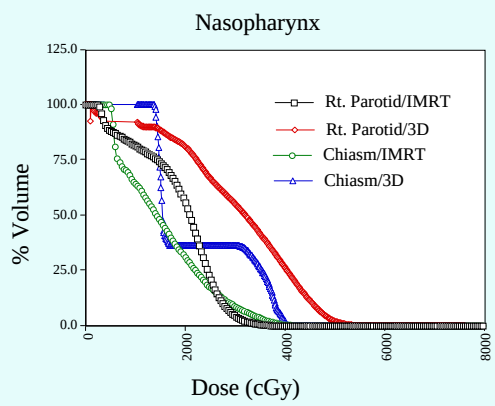
Plan/Vol	<5%	< 20%	< 30%	<50%
Forward	71.3	40.7	28.2	15.0 Gy
Corvus	74.0	43.5	30.2	12.4 Gy
MIMiC	54.5	23.3	18.0	9.0 Gy

75 Gy to 30% of rectum wall results in <10% RTOG grade II complication (estimated by Kutcher et. al.)

Clinical Comparisons - II

- Nasopharyngeal Carcinoma
  - 64 y.o. Chinese male with smoking history
  - T2B, N3, M0 classification
  - Left-sided mass bulging from lateral and posterior walls
- Dose constraints:
  - 70 Gy to GTV, 60 Gy to CTV
  - 45 Gy max to Cord/BS and optic chiasm
  - 30 Gy max to at least 50% of parotids
- Plan comparisons:
  - 10 fld 3D plan (Pinnacle) vs. IMRT w. Peacock MIMiC (Corvus)





Conclusions from Nasopharynx Comparison

- Dose to cord limits GTV dose for 3D plan
- Significantly better cord sparing with IMRT plan than with 3D plan
- Significantly better parotid sparing with IMRT
- Chiasm dose acceptable for both plans
- 100 % of GTV gets 70 Gy or more in IMRT, very little for 3D plan

Current Limitations with use of IMRT for Precision H/N Radiotherapy

- Patient immobilization and target localization
- 3D dose verification
- Treatment parameter verification
- Control of optimization process
- Efficient registration of biological imaging to Rx planning CT
- Accelerator control system efficiency
- MLC leaf positioning accuracy
- Dose calculation accuracy
- Dose delivery technology

Patient immobilization and target localization

- Dose gradients for IMRT are large in all directions so immobilization and target localization even more important than for 3DCRT
- Work in progress includes:
  - Imbedded markers, use of portal imagers and automated search routines to localize targets
  - Image subtraction for video images of patient vs. setup
  - Couch motions activated to reposition correctly on a daily basis using feedback
  - CT in treatment room (or on gantry) to verify plan before treatment
  - Motion prevention such as gated therapy for lung and thorax tumors

3-D Dose Verification

- Can only do single point or plane (film) dose verification at this time
- In the future:
  - Bang Gels read out by MR
  - Instrumented phantoms with multiple fixed points using diodes or very small ion chambers or MOS-FET
  - Portal imagers to image transmitted dose and programs to back-project information to patient
  - MV-CT using treatment beam

Treatment parameter verification

- Difficult to verify set of MLC position information for IMRT treatments
- In the future:
  - Use portal imagers to image intensity pattern and to verify MLC positions "on the fly"
  - Special programs to verify MU calculation per beam segment

Control of optimization process

- Inverse planning programs use desired dose constraints as input, but it is difficult to modify resulting plan and difficult to understand intensity patterns in the individual beams
- In the future:
  - Modify programs to allow feedback of physician critiques
  - Add ability to explicitly require dose uniformity to targets
  - Identify safe "dumping ground" for additional dose removed from sensitive normal structures
  - Include biological models for plan evaluation
  - Imbed inverse planning in fully functional 3D treatment planning with all required tools such as DRRs, etc.

Linear accelerator control and delivery systems

- IMRT has become possible because of the development of sophisticated linac control systems for automated delivery of large numbers of beams
- In the future:
  - Control systems will become faster and easier to use
  - Complex, multi-beam IMRT will be able to be delivered in conventional treatment times of < 15 minutes after setup
  - Leaf positioning and MU delivery per beam will be made more accurate

Dose calculation accuracy

- Currently, inverse planning programs have very simple dose calculation algorithms due to requirements of speed
- In the future:
  - Multiple calculation algorithms will be available to check plan during optimization process
  - Monte Carlo dose calculation program will become routinely available to evaluate the optimized plan
  - Speed of Monte Carlo will become so fast that it can be done <u>during</u> the optimization process (CORVUS will incorporate Peregrine Monte Carlo dose algorithm in the near future)

Workload - IMRT vs. 3DCRT

- Comparisons recently made of physics effort and treatment times for IMRT vs. 3DCRT for complex treatment plans
- Physics times were on average a factor of 3 higher than for 3DCRT (10 hours vs. 3 hours)
- IMRT treatment times somewhat longer on average than for 3DCRT (20 - 45 vs. < 15 min)
- Physician time somewhat greater for IMRT, mostly due to target contouring time (not documented)

Conclusions

- Conventional 3DCRT plans are adequate for many tumor/normal tissue situations
- Forward- and Inverse- planned IMRT with conventional or special MLCs are now practical
- Complex situations (such as H/N) can benefit significantly from IMRT
- Advances in control systems and planning systems will make IMRT easier and faster in the near future
- For now, IMRT should be saved for patients that can benefit the most from the technology

IMRT at UCSF - Philosophy

- IMRT should be saved for situations where the most sophisticated 3DCRT treatment planning cannot achieve a satisfactory result
- Complex IMRT should not be used if simple IMRT is adequate
- IMRT should only be used on patients with tumors in locations which can be well immobilized and easily positioned
- Increased dose heterogeneity within targets often observed with inverse planning in complex situations such as head/neck

UCSF Experience with IMRT- Conclusions to date

- Very complex IMRT treatments are practical to plan and implement when necessary
- Still takes an average of a factor of 2.5 - 3 more physics time to plan and verify IMRT than 3DCRT
- Most IMRT treatments can be finished within 20 minutes in-room time on either Varian or Siemens accelerators (up to 45 min. in exceptional cases)
- High dose regions of plan show agreement to within approximately 2% of calculations
- Low dose regions show typical discrepancies of 4-5% of maximum dose (measured > calculated) and larger discrepancies for more complex plans

UCSF Experience with IMRT- Conclusions to date

- Routine Monte Carlo calculations of expected dose distributions will be available in very near future with Peregrine and other programs
- Portal imager will soon be able to provide rapid, high contrast images to help verify patient and/or target position automatically
- Linac manufacturers working hard to make IMRT faster and dose delivery more accurate
- IMRT still not simple enough to be used in all clinics, but we are on the right track

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