AFTERWORD

From time to time, the imminent death of radiation oncology is announced, often by advocates of some treatment modality (immunology, gene therapy, and so forth) which is competing for research funds or for “market share.” Alas, these obituaries are premature. I say “alas” because we all must hope that some day a more effective approach to the cure of cancer will be discovered. One that will put radiotherapy out of business. A large proportion of my readers will have relatively close family members and friends who have been affected by cancer and they will understand how strong this hope is. Radiation therapy is a blunt and rough tool. It will not turn out to be the ultimate cure. It can, at best, only solve the problem of local, and not metastatic, disease. Its side effects are far from negligible. Our therapeutic gains, the fruit of much hard work over long years, are largely incremental in nature.

I have often been asked by young people contemplating entering the field of Radiation Oncology whether it is not a dead-end field in which employment opportunities and professional satisfaction will dwindle with time. Well, as I said, we hope that this will be so, sometime. But, unfortunately, that time does not seem near. Moreover, even if a highly effective biochemical or other cancer-antagonist is developed, it is likely that, for quite a while, it will be effective vis-à-vis microscopic disease, but not in eradicating the bulk tumor. This is because (1) the sheer burden of tumor cells is likely to be a problem, and (2) the mechanisms for delivery of the agent may be badly compromised in the tumor. For these reasons, it is likely that a tool to sterilize or debulk the gross tumor will be needed for a long time to come, which means that surgery and radiation therapy will continue to play a vital role in the treatment of cancer.

I have often thought that one of the great satisfactions of working in this field is that what one does can make a difference. I think of it as follows. Imagine that there is a universal curve that relates success to intensity of therapy, as in Figure A.1 below. A discipline that lies at a point such as A on the curve, for which one simply could not “get in” enough therapy, would likely be a depressing discipline to practice; the vast majority of one’s patients would do poorly. On the other hand, if one’s specialty lay at a point such as C, all one’s patients
would do well. This would certainly be pleasing, but one might feel that one’s patients would have improved without any special effort on one’s own part. Radiation oncology more nearly lies at a point such as B. If one is about halfway up the curve, where it is steepest, then one’s personal effort has an excellent possibility of improving results. This is, indeed, a charmed situation to be in. Although, one must admit, it has its drawbacks. If one takes credit for successes, then one must be prepared to accept at least partially responsibility for failures.

Several times in a professional lifetime, incautious “experts” are tempted to assert that their given field has reached a point of diminishing returns. That pretty much everything that is to be known has already been discovered. Don’t be deterred by such negativity; there’s much to be done. Molecular imaging and targeted therapies may radically change the practice. There is a lot to be gained by a much better understanding of the responses of normal tissues (and tumors) to a whole range of dose–volume distributions. Manipulation of the time factor – the number of fractions, their size, and overall duration of treatment – are important, but poorly understood, variables to be manipulated for the patient’s good. Enjoy these opportunities.

Please, resist the ever increasing pressure to be constrained by purely economic considerations. There is no lack of people worrying about finances and figuring out how to cut costs (and corners). Let yourself be an advocate for the patient.

I expect that the role of the individual will become more, rather than less, important. High technology, with good reason, is being brought into the field at an almost alarming rate. However, with increasing complexity and automation come increasing risks. Now, more than ever, both on the physics and medical sides, we need the critical eyes of experts blended with simple common sense to be cast over all that we attempt, and all that we do. The situation glimpsed in Figure 9.10 is not exaggerated; it is a warning – and an opportunity.

All in all, I have found the field of radiation oncology fascinating and personally rewarding, and I myself would have no hesitation to begin
again in these times. This book is written in the hope that it will catalyze or reinforce that same fascination in some of my readers. If you are in the field, or if you plan to enter it, then I’m sure you will have a fruitful, interesting, and enjoyable career.
ACKNOWLEDGEMENTS

We are very fortunate in our profession to be supported by a number of excellent scientific journals. In this connection, I want to mention, *inter alia*: the International Journal of Radiation Oncology, Biology, Physics; Radiotherapy and Oncology; Seminars in Radiation Oncology; Medical Physics; and Physics in Medicine and Biology. I have some idea of the enormous professional effort that the editors and reviewers put into bringing these journals out, month after month, and into keeping them to the highest possible standards. Anyone considering entering the field could do no better than to go to a library and look through a few recent issues of these journals.

A little while ago I went through the pleasant exercise of making a list of the people with whom I had collaborated over the years. I was astounded when I quickly reached the figure of 228. Obviously, it is impossible to recognize so many people individually, and invidious to select only a few. But, I do want to say that I have been enormously fortunate in the colleagues with whom I have worked. They have played a bigger part in writing this book than they know.

I must, however, single out one person, namely Herman Suit. He has been my teacher, colleague and friend for over a third of a century, and I have profited from his knowledge, style, and companionship.

With regard to the preparation of this book, I have had immeasurable help from a number of colleagues. I have bombarded them with questions, begged them for material, and asked them to review part or all of the manuscript. I want, therefore, to express my great gratitude to: Carlo Algranati, Thomas Bortfeld, George Chen, Paul deLuca, Lara Goitein, Bernie Gottschalk, Vincent Gregoire, Eugen Hug, Bleddyn Jones, Norbert Liebsch, Tony Lomax, Alejandro Mazal, Radhe Mohan, Andrzej Niemierko, Harald Paganetti, Eros Pedroni, Marco Schwarz, Steve Selzer, Joel Tepper, Howard Thames, Marcia Urie and Lynn Verhey.

Finally, it is my enormous pleasure to recognize the many contributions of my wife, Gudrun. She has supported me in writing this book at every step, and her review of the manuscript was invaluable to me. It is to her that this book is dedicated.
**ACRONYMS**

It is, unfortunately, almost impossible to avoid the use of acronyms in a technical field. The following is a list of those used in this book. “http://physics.nist.gov/cuu/Units/index.html” provides a convenient source of information on SI units.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>0D</td>
<td>zero-dimensional (a scalar quantity or number)</td>
</tr>
<tr>
<td>1D</td>
<td>one-dimensional</td>
</tr>
<tr>
<td>2D</td>
<td>two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>three-dimensional</td>
</tr>
<tr>
<td>3DCRT</td>
<td>three-dimensional conformal radiation therapy</td>
</tr>
<tr>
<td>4DCT</td>
<td>3DCT studies repeated at sequential times</td>
</tr>
<tr>
<td>A</td>
<td>mass number (no. protons &amp; neutrons in nucleus)</td>
</tr>
<tr>
<td>BEV</td>
<td>beam’s-eye view</td>
</tr>
<tr>
<td>CT</td>
<td>computed tomography</td>
</tr>
<tr>
<td>CTV</td>
<td>clinical target volume</td>
</tr>
<tr>
<td>DRR</td>
<td>digitally reconstructed radiograph</td>
</tr>
<tr>
<td>DVH</td>
<td>dose–volume histogram</td>
</tr>
<tr>
<td>EUD</td>
<td>equivalent uniform dose</td>
</tr>
<tr>
<td>FSU</td>
<td>functional sub-unit</td>
</tr>
<tr>
<td>GTV</td>
<td>gross tumor volume</td>
</tr>
<tr>
<td>HU</td>
<td>Hounsfield unit</td>
</tr>
<tr>
<td>IM</td>
<td>internal margin</td>
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<tr>
<td>IMPT</td>
<td>intensity-modulated proton therapy</td>
</tr>
<tr>
<td>IMRT</td>
<td>intensity-modulated radiation therapy</td>
</tr>
<tr>
<td>IMXT</td>
<td>intensity-modulated x-ray therapy</td>
</tr>
<tr>
<td>ITV</td>
<td>internal target volume</td>
</tr>
<tr>
<td>LET</td>
<td>linear energy transfer (“stopping power”)</td>
</tr>
<tr>
<td>MLC</td>
<td>multi-leaf collimator</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>MR</td>
<td>magnetic resonance</td>
</tr>
<tr>
<td>MRI</td>
<td>magnetic resonance imaging</td>
</tr>
<tr>
<td>MRS</td>
<td>magnetic resonance spectroscopy</td>
</tr>
<tr>
<td>NTCP</td>
<td>normal tissue complication probability</td>
</tr>
<tr>
<td>OAR</td>
<td>organ at risk</td>
</tr>
<tr>
<td>PET</td>
<td>positron emission tomography</td>
</tr>
<tr>
<td>POI</td>
<td>point of interest</td>
</tr>
<tr>
<td>PRV</td>
<td>planning risk volume</td>
</tr>
<tr>
<td>PTV</td>
<td>planning target volume</td>
</tr>
<tr>
<td>QA</td>
<td>quality assurance</td>
</tr>
<tr>
<td>RBE</td>
<td>relative biological effectiveness</td>
</tr>
<tr>
<td>RCT</td>
<td>randomized clinical trial</td>
</tr>
<tr>
<td>rf</td>
<td>radio-frequency</td>
</tr>
<tr>
<td>RVR</td>
<td>remaining volume at risk</td>
</tr>
<tr>
<td>SD</td>
<td>standard deviation (represented by the symbol $\sigma$)</td>
</tr>
<tr>
<td>SM</td>
<td>setup margin</td>
</tr>
<tr>
<td>SOI</td>
<td>surface of interest</td>
</tr>
<tr>
<td>TCP</td>
<td>tumor control probability</td>
</tr>
<tr>
<td>VOI</td>
<td>volume of interest</td>
</tr>
<tr>
<td>WYSIWYG</td>
<td>what you see is what you get</td>
</tr>
<tr>
<td>Z</td>
<td>atomic number (no. protons in nucleus)</td>
</tr>
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</table>
REFERENCES


Gottschalk B (2004) In: http://hwepl.harvard.edu/~gottschalk/ File named “pbs.pdf” can be extracted from BGdocs.zip


References


Seltzer S (1993) National Institute of Standards and Technology (NIST) technical note NISTIR 5221


INDEX

A
accuracy 16
anatomy 23–56
aperture 73, 236–237, 256–257
assessment [of plan]—see under
treatment plan
atlas of normal anatomy 55

B
beam of photons 4–6, 71–83
aperture 73
beam’s-eye view (BEV) 161–162
depth–dose distribution 73–77
design of 57–84
direction 163
non-coplanar 164
dose build-up 75
field shape, design of 160–162
field-size, influence on scattered
radiation 79–80
hardening 76
intensity-modifying device 73
inverse-square fall-off 76
lateral dose distribution 77–81
modality, choice of 160–161
penumbra 77–78
profile 77, 81
scattered photons 76–81
shaping 82
skin-sparing effect 75–76
weight 164
beam of protons—see proton beam
beam’s-eye view (BEV) 161–162
Bragg peak
electrons 222
protons 215–220
Bragg, Sir WH 213
Bragg, Sir WL 213
biophysical models—see models
blunder 15
bremsstrahlung
electrons—see under electron
interactions
protons—see under proton
interactions
build-up 75–76
bystander effect 93

C
clinical target volume (CTV) 25
combination therapy 2
comparison [of plans]—see under
treatment plan
compensator—see under proton
beam
Compton effect 60–61
computed tomography (CT) 29–43
and MRI 43–46
basis of reconstruction 30–32
CT/PET imager 47
four dimensional (4DCT) 37
Hounsfield unit (HU) 30, 35–36
Hounsfield unit to electron density
conversion 34
Hounsfield unit to water-
equivalent density conversion
259
planning CT 113
re-slicing 37
computer-driven planning 158
confidence—see uncertainty
confidence interval [or level]—see
under uncertainty
conformal avoidance 179
constraints—see under treatment
plan and under optimization
conviction 292–293
Cormack, A 8, 178
coronal section 37, 123
couch 4
Coulomb, C-A de 63

323
Coulomb interaction
electrons 67
protons—see under proton interactions
cross-firing beams 6, 274

D
delineation of anatomy 52–56, 113
automatic feature extraction 53
display of 121
manual 52
uncertainty in 54–55
uninvolved normal tissues 53
digitally-reconstructed radiograph (DRR) 38–39, 145, 147
documentation [of treatment] 114
dose 5, 67
calculation of photons 83–84
protons 260
energy deposited as chemical changes 68
energy deposited as heat 68
surrogate for biological effects 86
temperature rise due to 68
dose bath 279–280
dose disposal—see under treatment plan
dose mottle 240
dose representation 119–128
0D dose representation 126–128
1D dose representation 125–126
2D dose representation 121–122
3D dose representation 123–125
4D dose representation 120–121
color-wash 122
dangers of 131–132
dose-difference display 133, 280
dose statistics 126–128
$D_V$ 127
$D_{\text{min}}$ 127
$D_{\text{near-min}}$ 127
$D_{\text{mean}}$ 127
$D_{\text{max}}$ 127
$D_{\text{near-max}}$ 127
$V_D$ 127
dose summarization 126
dose-volume histogram (DVH)—see dose-volume histogram
information, loss of 120, 126
interactivity 124
isodose contours 122
time variation 124–125
dose uncertainty
(calculation of 171–172
in quantities derived from dose, 174
protons 271
visualization of 122, 172–174
dose-volume effect 7, 89
dose-volume histogram (DVH) 125–126
crossing DVHs 168
cumulative 125
differential 125
dose-volume models for normal tissues (NTCP)—see under models
dose-volume models for tumors (TCP)—see under models
$D_V$ 127

E
Einstein, A 59, 61
electron interactions 63–66
bremsstrahlung 65, 72
damage is due to secondary electrons 69
excitation 64
ionization 64
number of ionizations 69
scattering by nuclei 65
electron transport 78
electron volt 58
equivalent uniform dose (EUD) 96–97, 103
error 14–15
error function 225
established experience 87–88
exponential attenuation 74

F
feature 52
feature extraction 53
field 5, 79
fluence 5
fluoroscopy 37
flux 5
fraction 3, 89, 101, 117
fractionation—see fraction
full-width at half-maximum 225

G
gantry 4
Gray (Gy) 5, 67
gross tumor volume (GTV) 25

H
Heviside function 202
hint 291
Hounsfield unit (HU) 30, 35–36

I
image
  coronal 37, 123
  motion, impact on 148
  projection 29
  sagittal 37, 123
  sectional 29
  transverse 37, 123
image enhancement 35–36
  importance of interactivity 35–36
  level 35–36
  window 35–36
image registration 48–51
  deformable 50
  hat and head 49
  mutual information 50
  point-to-point 49
  rigid body 48
  surface-to-surface 49
  voxel-to-voxel 50
immobilization—see under motion
inhomogeneities 248–256, 265–268
  complex inhomogeneities 255–256, 266
  degradation of Bragg peak 255, 266
  infinite slab 249–250
  photons, impact on 249–250
  semi-infinite slab 249, 250–252
  sliver 249, 252–254
  uncertainty analysis 255–256
integral dose 165–167, 274
interplay effect 240–241
intensity-modifying device 73
interactions
  of electrons—see electron interactions
  of photons—see photon interactions
  of protons—see proton interactions
internal margin (IM) 25
internal target volume (ITV) 25
intensity 5
intensity-modulated proton therapy (IMPT)—see under proton treatment plan
intensity-modulated radiation therapy (IMRT) 8, 116, 177–210
  conformal avoidance 179
  constrained optimization 193–194
  forward planning 182
  IMRT plan 179–180
  inverse planning 180–182
  magnitude of the optimization problem 185–186
  objective function 183
  optimization? 209–210
    mathematical meaning 209–210
    vernacular meaning 209–210
  voting for the best 209
planning IMRT 183–185
score 9, 183, 190–197
  biophysical models 193
  combining tumor and normal tissue responses 195–197
  complexity of plan 192
  normal tissues, impact of plan on 192, 195
  optimization of 193
  patient’s-eye view 197
  scoring a plan 186–197
  tumor, impact of plan on 191–192, 194–195
  uncomplicated control 196–197
  what is often not in the score 188–190
  why score? 187–188
score function 9, 183
search [for optimum score] 183, 197–208
  buried biology 208
  conjugate gradient method 199
direction set optimization 199–202
global minimum 201
landscape 197–198
local minimum 201
mean-square dose deviations 201–202
Pareto optimization 204
re-optimization 207–208
scale 205–206
simulated annealing 202–204
starting values 205
steepest descent, method of 199
tradeoffs 118, 202, 204, 207
intensity-modulated X-ray therapy (IMXT)—see intensity-modulated radiation therapy
intensity profile 5
International Commission on Radiation Units and Measurement (ICRU) 25
terms for volumes of interest 25–28
ionization 64
ionization chamber 67, 243
L
Larmor frequency 40, 41
level 35–36
linac 4, 71
linear energy transfer (LET) 216, 260
local treatment 1–2
localization—see under motion
M
magnetic resonance—see magnetic resonance imaging
magnetic resonance imaging 40–43
and CT 43–46
Larmor frequency 40, 41
proton-density 42
spectroscopy (MRS) 43
T1-weighted 42
T2-weighted 42
manual treatment planning 157–175
margin design—see under motion
Maxwell, JC 41
models 9, 87–91
caveats 104–110
equivalent uniform dose (EUD) 96–97
endpoint 109
fractionation 109
mean dose 109
normal tissue complication probability 105–110
paired organs 108–109
parallel architecture 107–110
serial architecture 105–107
tumor control probability 104
clinical data 99
cylindrical organs 108
dose-volume effect 7, 89
empirical models 91
IMRT, use of models in 193
margin design, applied to 151–153, 155
mechanistic models 91
normal tissue complication probability (NTCP) 98–103, 105–110
critical-element model 101
empirical models 91, 103
endpoint 109
equivalent uniform dose (EUD) 103
mechanistic models 91, 99–103
parallel architecture model 102, 107–110
serial architecture model 101–102, 105–107
paired organs 108–109
skepticism concerning 90
tissue architecture 100
functional sub-unit (FSU) 100
graded response 100
parallel 100
planning, influence on 168–170
serial 100
tubular organs 108
tumor control probability (TCP) 91–97
boost dose 95–96
empirical models 91, 96–97
equivalent uniform dose (EUD) 96–97
mean dose 92–93, 109
mechanistic models 91, 93–96
minimum dose 92–93
underdose 95
Monte Carlo 84, 253
motion 139–155
  compensation for organ motion 150–155
  imaging, impact of motion on 148
  immobilization 141–143
    bite-block 142–143
    proton therapy 271
  stereotactic head holder 143
  thermoplastic mask 142
  two-joint rule 141
  whole-body 142
inter-fraction motion 147–148
interplay effect 240–241
repaing 241
intra-fraction motion 148
localization 143–146
  bony landmarks 144–146
  DRR-based 145
  markers 146
  skin marks 143–144
margin design 150–153, 155
organ motion 147–155
respiration gating 149
tumor tracking 149–150
random motion 153–155
systematic motion 153–155
verification 146–147
  portal radiographs 146–147
  proton therapy 271
  X-radiography 147
multi-leaf collimator (MLC) 82, 83, 119, 237
multiple beams—see cross-firing beams

N
near-forward direction 60
normal tissue complication probability (NTCP)—see under models

O
objective function 183
ocular melanoma 281–283
organ at risk (OAR) 27
optimization [of photon plans]—see intensity-modulated proton therapy
optimization [of proton plans]—see intensity-modulated proton therapy

P
pair production 61–62
patient’s-eye view 174–175, 197
pencil beam—see under proton beam
photo-electric effect 59–60
photons 2, 58
  beam of—see beam of photons
plan
  photons—see treatment plan
  protons—see proton treatment plan
planning aims 115–118
planning risk volume (PRV) 27
planning target volume (PTV) 25, 268–269
point of interest (POI) 28
Poisson statistics 92
positron 46
  annihilation of 46
positron emission tomography (PET) 46–48
  CT/PET imager 47
precision 16
prescription 9, 113–115, 118
prescription dose 115–116
probability density function 16
proton beam
  aperture design 256, 257
    virtual aperture 256
  beam delivery 229–242
    compensator 235, 256, 257–259
feathering in angle 258, 267
feathering in depth 268, 276
Hounsfield unit conversion 259
smearing 258
virtual compensator 256
water-equivalent density 259–260
depth-dose 215–222, 223–224
Bragg peak 215–220
distal “penumbra” 219–220
energy loss due to Coulomb interactions 216–217
energy spread of beam 217, 218–220
inverse-square effect 221
nuclear interactions 217–218
peak-to-plateau dose ratio 219
pencil beam 223–224
range 218
range straggling 217
spread-out Bragg peak (SOBP) 220–222
field 5, 79
inhomogeneities, influence of—see inhomogeneities
lateral dose distribution 225–228
large angle Coulomb scattering 226
material upstream 227–228
multiple Coulomb scattering 225–226
nuclear interactions 226–227
penumbra 228
pencil beam 8, 223–224, 225–228
finite 223
infinitesimal 223
use of 224
scanned beam—see proton therapy equipment
scattered beam—see proton therapy equipment
wobbled beam—see proton therapy equipment

proton dosimetry 242–245
absolute 243–244
relative 244–245

proton interactions 213–215
Bremsstrahlung 214
combined effects 228–229
Coulomb interactions with electrons 213, 216–217
Coulomb interactions with nuclei 213–214
large angle Coulomb scattering 226
multiple Coulomb scattering 225–226
linear energy transfer (LET) 216
nuclear interactions with nuclei 214–215, 217–218, 226–227
elastic 214
non-elastic 214
relative biological effectiveness (RBE)—see relative biological effectiveness
stopping power 216

proton therapy equipment 229–242
accelerator 230–231
beam control 242
beam monitoring 242, 244
beam transport system 231
gantry 232–233
safety 242
scanned beam delivery system 237–241
current status of 241
intensity-modulated proton therapy, used for 238
interplay effect 240, 241
repainting 241
spot scanning 238
virtual sources 221
scattered beam delivery system 233–237
aperture 236–237, 256–257
compensator 235, 256, 257–259
depth tailoring 235
double scattering 234–235
lateral enlargement 233–235
low energy protons from aperture edges 236
range modulator 235
wobbled beam 241

proton treatment plan 262–273
comparisons with photons 274, 277–280
differences from photons 262–273
complex geometry 265
dose bath 279–280
inhomogeneities 265–268
large targets 265
lung, overshoot in 266
metal implants 267
planning target volume
268–269
dose distributions achievable
273–280
good beam directions 267
intensity-modulated proton
therapy (IMPT) 270–271, 276–280
distal edge tracking 278
dose bath 279–280
ocular melanoma, treatment of
281–283
relative biological effectiveness
(RBE)—see relative biological
effectiveness
protons, clinical experience 283–285

Q
quadrature 20
quality assurance 287–288
protons, special issues 272–273
quality control 287

R
relative biological effectiveness RBE
[of protons] 260–262
constant value of 1.10 261
dependence on LET 260
deviations from 1.10 262
RBE-weighted dose 261
record [of treatment] 113
record and verify 136
registration—see image registration
remaining volume at risk (RVR) 28, 129
repainting 241
report [of treatment(s)] 113
risk 21

S
safety 10
safety margin (SM) 14
sagittal section 37,123
scanned beam—see under proton
therapy equipment
scattered beam—see under proton
therapy equipment
scattering of electrons by nuclei 65
score—see under intensity-modulated
radiation therapy
score function 9, 183
setup margin (SM) 25
skin-sparing effect 75–76
standard deviation (SD) 16, 17
standard uncertainty 17
relative 17
statistical significance 18, 290–291
stopping power 216
sum in quadrature 20
surface of interest (SOI) 28

target volume 3
technical data 113, 119
therapeutic ratio 88

therapy machine
60Co machine 71
effective energy 72
electron linear accelerator (linac) 4, 71
flattening filter 72
orthovoltage 76
simulator 135
supervoltage 88

Tobias, C 30
tradeoffs 118, 202, 204, 207
transverse section—see under image
treatment plan 9, 10, 111–137, 112
archiving 114
assessment of a plan 114, 128–130
expert inspection 128
manual inspection 128
beam—see under beam of photons
beam’s-eye view (BEV) 161–162
comparison of plans 130–135
biophysical models 134
dose difference display 133, 280
dose statistics 134
DVHs 133–134
score—see under intensity-modulated radiation therapy
side-by-side dose display 130–132
computer-driven treatment planning 158
documentation 114
dose disposal 164–170
  a lot to a little or a little to a lot? 167–168
tissue architecture, influence of 168–170
dose, representation of—see dose representation
field shape, design of 160–162
integral dose 165–167, 274
iteration of planning process 164
manual treatment planning 157–175
modality, choice of 160–161
number of 162
optimization—see intensity-modulated radiation therapy
patient’s-eye view 174–175
planning aims 115–118
planning CT 113
planning process 113–114
prescription 9, 113, 114, 115, 118
prescription dose 115–116
protons—see proton treatment plan
record [of treatment] 113
report [of treatment] 113
segment 117
segment dose 117
simulator 135
technical data 113, 119
tradeoffs 118, 202, 204, 207
uncertainty—see dose uncertainty
uniform-intensity radiation therapy 178
trend 291–292
true value 17
tumor control probability (TCP)—see under models
two-joint rule—see under motion

U
uncertainty 13–22, 289–302
denumerable 13
display of 122
combined 20
confidence level [or interval] 16–19, 290–293
conviction 292–293
hint 291
statistical significance 18, 290–291
trend 291–292
dose—see dose uncertainty
error 14–15
hypothesis testing 293–295
law number 1 21
law number 2 22
probability density function 16
P-value 290, 296
random error 15
randomized clinical trial (RCT) 295–302
  compact with patient 298
cost-benefit trials 301
equipoise 297–298
systematic error 15
type A 15
type B 15

V
V_D 127
verification—see under motion
volume of interest (VOI) 28
voxel 31

W
weight [of a beam] 112, 164
Wilson, RR 212, 220
window 35–36
wobbled beam—see under proton therapy equipment