DOI:10.3969/j.issn.1005-202X.2017.02.010

医学放射物理

Monaco设计直肠癌固定机架角调强和容积旋转调强治疗的剂量学比较

孙永健,曹洋森,代智涛,于春山,王强,谢红亮,刘永明
上海长海医院放疗科,上海 200433

【摘 要】目的:对比Monaco治疗计划系统设计7野静态调强(Step & Shoot IMRT)、7野动态调强(DMLC IMRT)及容积旋转调强(VMAT)在直肠癌中的剂量学差异。**方法:**回顾分析13例Monaco设计的直肠癌患者,行CT模拟定位并勾画靶区和危及器官。相同优化条件下分别使用7野Step&Shoot、7野DMLC及VMAT进行剂量优化和评估。比较两种优化模式的靶区剂量、适形指数(CI)、均匀指数(HI)和危及器官受量。**结果:**与7野Step&Shoot计划相比较,7野DMLC及VMAT计划很大程度上提高了靶区内剂量分布的均匀性,HI均有所降低,PGTV的CI也有所提高。7野DMLC计划可以获得更加良好的靶区剂量分布,对于PCTV的D_{min}、V_{45}及CI,Step&Shoot也有所提高,差异有统计学意义(P<0.05)。7野DMLC和VMAT计划使膀胱、小肠的平均剂量D_{mean}、小肠的V_{30}有所降低;DMLC计划更好地降低了膀胱D_{max}和小肠V_{40};VMAT计划更好降低了右侧股骨头D_{mean}的剂量和左侧股骨头D_{max}及V_{40},差异均有统计学意义(P<0.05)。DMLC和VMAT计划总机器跳数、计划子野数均有所增加,DMLC计划治疗时间有所增加,VMAT计划则有所减少,差异均具有统计学意义(P<0.05)。**结论:**在使用Monaco设计直肠癌的治疗计划时,推荐使用VMAT治疗方式以获得好的剂量分布和治疗效率。

【关键词】容积旋转调强;静态调强;动态调强;剂量分布;直肠癌
【中图分类号】R811.1　**【文献标志码】**A　**【文章编号】**1005-202X(2017)02-0161-05

Dosimetric comparison of seven-field intensity modulated radiotherapy and volumetric modulated arc therapy for rectal cancer designed with Monaco

SUN Yongjian, CAO Yangsen, DAI Zhitao, YU Chunshan, WANG Qiang, XIE Hongliang, LIU Yongming
Department of Radiation Oncology, Shanghai Changhai Hospital, Shanghai 200433, China

Abstract: Objective To compare the dosimetric differences of 7-field (7F) Step & Shoot intensity-modulated radiotherapy (IMRT), 7F dynamic multi-leaf collimator (DMLC) IMRT, and volumetric modulated arc therapy (VMAT) designed in Monaco treatment planning system for rectal cancer. **Methods** CT simulation location was performed and target areas and organs-at-risk (OARs) were delineated for 13 patients with rectal cancer. With the same optimization conditions, 7F Step & Shoot IMRT, 7F DMLC IMRT and VMAT designed in Monaco system were used for dose optimization and evaluation. The dose to target areas and OARs, conformal index (CI), heterogeneous index (HI) were compared. **Results** Compared with 7F Step & Shoot IMRT plan, 7F DMLC IMRT and VMAT plans showed greatly improved the homogeneity of dose distribution inside target areas, reduced HI, and better CI of planning gross target volume. 7F DMLC IMRT plan achieved a better dose distribution in target areas, and 7F Step & Shoot IMRT also showed higher D_{min}, V_{45} and CI of planning clinical target volume, with statistical significance (P<0.05). 7F DMLC IMRT and VMAT plans achieved lower D_{mean} of the bladder and intestine, and V_{30} of the intestine. 7F DMLC IMRT plans decreased the D_{max} of the bladder and V_{40} of the intestine, while VMAT plans decreased the D_{mean} of the right femoral head, and D_{max} and V_{40} of the left femoral head (P<0.05). 7F DMLC IMRT and VMAT plans showed increased monitor units and segments. The treatment time was longer in 7F DMLC IMRT plan, but shorter in VMAT plan (P<0.05). **Conclusion** VMAT plans which can archive a better target dose distribution and efficiency is recommended when the Monaco treatment planning system was used to design radiotherapy plan for rectal cancer.

Keywords: volumetric modulated arc therapy; Step & Shoot intensity-modulated radiotherapy; dynamic multi-leaf collimator intensity-modulated radiotherapy; dose distribution; rectal cancer

【收稿日期】2016-10-24
【作者简介】孙永健,男,主管技师,研究方向:肿瘤放射物理。E-mail: yian529@163.com
【通信作者】刘永明,男,主管技师,研究方向:肿瘤放射物理。E-mail: liuymsh@163.com

前 言

直肠癌是消化系统常见的恶性肿瘤之一。在美国，结直肠癌位列癌症新增病例第3位，死亡病例第3位，2016年预计将新增134 490例，死亡49 190例[1]。在中国，2015年预计新增结直肠癌376 300例，死亡191 000例[2]。直肠癌术前放疗可以有效降低肿瘤局部复发概率，提高手术保肛率[3]。由于肿瘤靶区(GTV)和临床靶区(CTV)体积较大，形状复杂，毗邻危及器官(OAR)，固定机架角调强放疗(IMRT)技术已广泛应用于直肠癌的放射治疗，在降低OAR受量的同时可以实现靶区局部同步增量[4]。容积旋转调强(VMAT)技术在获得调强剂量分布的同时缩短了治疗时间，提高了治疗效率[5]。Monaco治疗计划系统配备有蒙特卡罗(Monte Carlo)算法，也是目前放射治疗计划系统(TPS)中公认最精确的剂量计算算法[6-7]。本研究旨在比较7野静态调强(Step & Shoot IMRT)、7野动态调强(DMLC IMRT)及一个完整弧旋转容积调强(1 arc VMAT)在Monaco设计直肠癌治疗计划中的剂量学差异。

1 材料与方法

1.1 临床资料

回顾性分析2015年1月~12月期间13例直肠癌患者临床资料。男性患者6例，女性患者7例，中位年龄60岁(30~80岁)，病理类型均为腺癌。

1.2 定位方法

患者采用真空垫固定，仰卧位，双手抱头。使用荷兰飞利浦公司16排大孔径CT模拟定位机扫描定位。扫描范围从L1椎体至坐骨结节下5 cm，扫描条件为120 kVp、400 mAs、5 mm层厚无间隔螺旋扫描。定位前1小时排空膀胱，口服500 mL温开水。扫描完成后CT影像传送至Monaco治疗计划系统(TPS)。

1.3 靶区和危及器官勾画

由临床医师在每例患者CT图像上进行肿瘤病灶(GTV)和高危淋巴引流区域临床靶区(CTV)的勾画。由物理师将GTV和CTV各向均匀外放5 mm得到计划肿瘤靶区(PGTV)和计划临床靶区(PCTV)。OAR勾画包括小肠、双侧股骨头和膀胱。勾画均参照国际辐射单位和测量委员会(ICRU)83号报告的定义进行[8]。

1.4 治疗计划系统与治疗设备

治疗计划系统采用瑞典医科达公司的Monaco 5.11.0。直线加速器使用瑞典医科达公司配备40对多叶准直器(MLC)的Synergy机型。

1.5 处方剂量和计划设计

对每例患者分别给予PGTV处方剂量50 Gy，PCTV处方剂量45 Gy，25分次的同步增量放疗。所有计划均使用6 MV X射线。使用同样目标优化参数分别设计7野Step & Shoot IMRT、7野DMLC IMRT以及1 arc VMAT计划。

1.6 治疗计划评估

所有计划均取95%以上PGTV满足处方剂量50 Gy进行归一。使用剂量体积直方图(DVH)进行靶区和危及器官的剂量评估。靶区剂量评估参数包括PGTV所接受的最大剂量D_{max}、最小剂量D_{min}、平均剂量D_{mean}、50 Gy等剂量线所包绕体积V_{50}、52.5 Gy等剂量线所包绕体积$V_{52.5}$、适形指数(CI)、均匀指数(HI)以及PCTV的D_{max}、D_{min}、D_{mean}、45 Gy等剂量线所包绕体积V_{45}、CI、HI。其中$CI=V_{RX}^2/(TV \cdot V_{RI})$，式中$V_{RX}$为处方剂量覆盖的靶区体积，TV为靶区体积，$V_{RI}$为处方剂量等剂量线所包绕的体积。$HI=D_{5\%}/D_{95\%}$，式中$D_{5\%}$为最热5%的靶区所接受的剂量，$D_{95\%}$为靶区95%体积所接收到的最小剂量。危及器官受量评估参数包括：膀胱、小肠、左右股骨头的D_{max}、D_{mean}、30 Gy等剂量线所包绕体积V_{30}、40 Gy等剂量线所包绕体积V_{40}。计划参数评估参数包括总机器跳数MUs、治疗时间Time和总子野个数Segments。

1.7 统计方法

数据以$\bar{x} \pm s$表示。采用SPSS 21统计软件进行数据处理，对两种算法计算结果的参数比较采用配对t检验。$P<0.05$为差异有统计学意义。

2 结 果

2.1 靶区剂量学差异

7野Step&Shoot、7野DMLC及1 arc VMAT的靶区剂量比较结果列于表1。由表1可知，7野DMLC和VMAT的治疗计划相比于7野Step&Shoot计划，PGTV D_{max}、D_{mean}、PCTV D_{max}、D_{mean}的剂量均有所降低，差异有统计学意义($P<0.05$)；PGTV D_{min}的剂量均有所提高，差异有统计学意义($P<0.05$)；PGTV和PCTV的HI有所降低，PGTV的CI有所提高，差异有统计学意义($P<0.05$)。7野DMLC计划相比于7野Step&Shoot计划，PCTV D_{min}的剂量和处方剂量体积V_{45}以及CI均有所提高，差异有统计学意义($P<0.05$)。其余评估指标差异均没有统计学意义($P>0.05$)。

2.2 OAR剂量学差异

7野Step&Shoot、7野DMLC及1 arc VMAT的

表1　7野Step&Shoot、7野DMLC及1 arc VMAT的靶区剂量学差异(n=13, $\bar{x} \pm s$)

Tab.1 Dose differences in target areas among 7F Step & Shoot IMRT, 7F DMLC IMRT and 1 arc VMAT plans (*n*=13, *Mean±SD*)

Target area	Parameter	7F Step & Shoot IMRT	7F DMLC IMRT	1arc VMAT
PGTV	D_{max}/Gy	54.07±0.30	53.65±0.29	53.72±0.45
	P value	-	0.002	0.018
	D_{min}/Gy	48.49±0.35	48.91±0.16	48.74±0.21
	P value	-	0.002	0.047
	D_{mean}/Gy	51.25±0.18	50.96±0.12	51.06±0.20
	P value	-	0.000	0.033
	V_{50}/%	95.00±0.00	95.00±0.00	95.00±0.00
	P value	-	-	-
	$V_{52.5}$/%	14.57±25.48	1.36±1.18	2.57±4.42
	P value	-	0.090	0.127
	CI	0.59±0.10	0.70±0.12	0.65±0.11
	P value	-	0.000	0.005
	HI	1.05±0.01	1.04±0.01	1.04±0.01
	P value	-	0.001	0.032
PCTV	D_{max}/Gy	54.09±0.30	53.71±0.33	53.73±0.45
	P value	-	0.003	0.017
	D_{min}/Gy	41.92±0.50	43.09±0.44	41.89±1.46
	P value	-	0.000	0.923
	D_{mean}/Gy	47.26±0.43	46.97±0.35	47.02±0.31
	P value	-	0.000	0.000
	V_{45}/%	94.24±4.01	96.34±3.59	94.31±3.96
	P value	-	0.001	0.934
	CI	0.81±0.04	0.85±0.04	0.84±0.04
	P value	-	0.000	0.165
	HI	1.13±0.02	1.12±0.02	1.13±0.02
	P value	-	0.000	0.013

7F: Seven fields; IMRT: Intensity-modulated radiotherapy; VMAT: Volumetric modulated arc therapy; PGTV: Planning gross target volume: PCTV: Planning clinical target volume; HI: Heterogeneous index; CI: Conformal index

OAR剂量比较结果列于表2。由表2可知，7野DMLC和VMAT的治疗计划相比于7野Step&Shoot计划，膀胱、小肠的平均剂量D_{mean}有所降低，小肠的V_{30}也有所降低，差异有统计学意义(P<0.05)。7野DMLC计划相比于7野Step&Shoot计划，膀胱D_{max}的剂量和小肠V_{40}的体积均有所降低，差异有统计学意义(P<0.05)。VMAT计划相比于7野Step&Shoot计划，右侧股骨头D_{mean}的剂量和左侧股骨头D_{max}及V_{40}均有所降低，差异有统计学意义(P<0.05)。其余评估指标差异均没有统计学意义(P>0.05)。

2.3 计划机器参数差异

7野Step&Shoot、7野DMLC及1 arc VMAT的机器参数差异比较结果列于表3。由表3可知，7野DMLC和VMAT的治疗计划相比于7野Step&Shoot计划，总机器跳数MUs有所增加，差异有统计学意义(P<0.05)；计划子野数Segments也有所增加，差异均有统计学意义(P<0.05)。7野DMLC计划相比于7野Step&Shoot计划，治疗时间Time有所增加；VMAT计划相比于7野Step&Shoot计划，治疗时间Time有所减少，差异均有统计学意义(P<0.05)。

3 讨 论

调强放射治疗已经成为直肠癌综合辅助治疗中的一个重要环节[9-10]。VMAT是近年来被普遍看好的一种新的调强放疗技术，它在出束照射的过程中，通过治疗机架的弧形旋转和多叶准直器的动态运动，实现了射野方向、大小、形状的动态变化，同时治疗剂量率连续变化，实现了靶区的快速调强。

表2 7野Step&Shoot、7野DMLC及1 arc VMAT的OAR剂量学差异(n=13, $\bar{x}\pm s$)

Tab.2 Differences in the doses to organs-at-risk (OARs) among 7F Step & Shoot IMRT, 7F DMLC IMRT and 1 arc VMAT plans (n=13, *Mean±SD*)

OARs	Parameter	7F Step & Shoot IMRT	7F DMLC IMRT	1arc VMAT
Bladder	D_{max}/Gy	48.67±0.93	48.18±1.03	48.22±0.45
	P value	-	0.020	0.075
	D_{mean}/Gy	33.29±2.74	33.56±2.86	33.68±3.20
	P value	-	0.000	0.033
	V_{30}/%	62.21±10.91	62.84±10.97	63.53±12.05
	P value	-	0.457	0.180
	V_{40}/%	37.75±12.20	37.91±12.25	38.42±12.59
	P value	-	0.685	0.231
Intestine	D_{max}/Gy	47.83±0.79	47.63±0.87	48.35±1.18
	P value	-	0.160	0.118
	D_{mean}/Gy	31.09±2.26	30.04±2.35	29.91±2.61
	P value	-	0.000	0.001
	V_{30}/%	53.92±9.66	49.07±10.27	49.15±10.37
	P value	-	0.000	0.001
	V_{40}/%	25.04±7.90	22.49±7.88	23.45±8.28
	P value	-	0.001	0.095
Femoral head-R	D_{max}/Gy	43.68±1.55	44.12±1.19	43.48±1.49
	P value	-	0.122	0.345
	D_{mean}/Gy	23.59±1.50	23.35±1.56	22.07±1.93
	P value	-	0.220	0.003
	V_{30}/%	18.29±4.06	18.24±4.16	16.25±6.17
	P value	-	0.933	0.107
	V_{40}/%	2.13±1.68	2.47±1.73	2.03±1.82
	P value	-	0.206	0.729
Femoral head-L	D_{max}/Gy	44.00±1.58	44.09±1.49	42.84±1.74
	P value	-	0.831	0.001
	D_{mean}/Gy	24.35±1.60	24.13±1.63	24.60±2.00
	P value	-	0.237	0.493
	V_{30}/%	20.05±5.04	19.60±5.19	17.50±7.44
	P value	-	0.530	0.089
	V_{40}/%	2.69±2.00	3.08±2.17	1.64±1.32
	P value	-	0.128	0.007

表3 7野Step&Shoot、7野DMLC及1 arc VMAT的机器参数差异(n=13, $\bar{x}\pm s$)

Tab.3 Differences in machine units (MU) among 7F Step & Shoot IMRT, 7F DMLC IMRT and 1 arc VMAT plans (n=13, *Mean±SD*)

Item	7F Step & Shoot IMRT	7F DMLC IMRT	1 arc VMAT
MU	577.25±73.21	710.22±62.97	810.18±53.90
P value	-	0.000	0.000
Time/s	411.92±30.49	440.92±23.38	223.64±18.39
P value	-	0.007	0.000
Segments	83.31±10.93	263.77±3.39	153.85±5.97
P value	-	0.000	0.000

使用相同的初始优化条件，分别使用7野Step&Shoot、7野DMLC及VMAT进行计划优化，得到不同剂量分布的优化结果。3种治疗计划均可满足临床治疗的需要。7野DMLC及VMAT计划很大程度上提高了靶区内剂量分布的均匀性，HI均有所降低，PGTV的CI也有所提高。7野DMLC相比VMAT计划可以获得更加良好的靶区剂量分布，PCTV的D_{min}、V_{45}及CI也有所提高，VMAT计划在这3个指标上差异则无统计学意义。OAR方面7野DMLC及VMAT均可以有效降低膀胱、小肠的D_{mean}以及小肠的V_{30}。故从靶区和危及器官受量方面分析，7野DMLC可以获得最佳的剂量分布，VMAT则略次于7野DMLC计

划。但从机器治疗效率方面分析，7野DMLC及VMAT计划的MUs和子野数相比较7野Step&Shoot都会有所增加，7野DMLC平均治疗时间长于7野Step&Shoot，VMAT平均治疗时间只需223.64 s，远远小于7野Step&Shoot的411.92 s和7野DMLC的440.92 s。更短的治疗时间可以减少患者不确定运动带来的治疗误差，同时提高了治疗效率。纵观全局，在使用Monaco设计直肠癌的调强治疗计划时，推荐使用VMAT治疗技术以获得更好的剂量分布和治疗效率[11]，若更加关注于靶区剂量分布，推荐使用DMLC动态调强技术。

【参考文献】

[1] SIEGEL R L, MILLER K D, JEMAL A. Cancer statistics, 2016[J]. CA Cancer J Clin, 2016, 66(1): 7-30.

[2] CHEN W, ZHENG R, BAADE P D, et al. Cancer statistics in China, 2015[J]. CA Cancer J Clin, 2016, 66(2): 115-132.

[3] 俞静, 曹邦伟, 林清, 等. 局部晚期直肠癌术前同步放化疗临床意义的初步探讨[J]. 中华肿瘤防治杂志, 2012, 19(15): 1173-1176.
YU J, CAO B W, LIN Q, et al. Management of locally advanced rectal cancer with preoperative three-dimensional conformal radiotherapy combined with chemotherapy [J]. Chinese Journal of Cancer Prevention and Treatment, 2012, 19(15): 1173-1176.

[4] SAMUELIAN J M, CALLISTER M D, ASHMAN J B, et al. Reduced acute bowel toxicity in patients treated with intensity-modulated radiotherapy for rectal cancer[J]. Int J Radiat Oncol Biol Phys, 2012, 82(5): 1981-1987.

[5] OTTO K. Volumetric modulated arc therapy: IMRT in a single gantry arc[J]. Med Phys, 2008, 35(1): 310-317.

[6] DENG J, GUERRERO T, MA C M, et al. Modelling 6 MV photon beams of a stereotactic radiosurgery system for Monte Carlo treatment planning[J]. Phys Med Biol, 2004, 49(9): 1689-1704.

[7] FIPPEL M, HARYANTO F, DOHM O, et al. A virtual photon energy fluence model for Monte Carlo dose calculation[J]. Med Phys, 2003, 30(3): 301-311.

[8] Prescribing, recording, and reporting photon-beam intensity-modulated radiation therapy (IMRT): contents[J]. Journal of the ICRU, 2010, 10(1): 1-106.

[9] ROH M S, COLANGELO L H, O'CONNELL M J, et al. Preoperative multimodality therapy improves disease-free survival in patients with carcinoma of the rectum: NSABP R-03[J]. J Clin Oncol, 2009, 27(31): 5124-5130.

[10] SAUER R, LIERSCH T, MERKEL S, et al. Preoperative *versus* postoperative chemoradiotherapy for locally advanced rectal cancer: results of the German CAO/ARO/AIO-94 randomized phase III trial after a median follow-up of 11 years[J]. J Clin Oncol, 2012, 30(16): 1926-1933.

[11] 杨咏强, 冯林春, 王运来, 等. 直肠癌术前容积旋转调强放疗和螺旋断层放疗的剂量学比较[J]. 解放军医学院学报, 2014, 35(2): 146-149.
YANG Y Q, FENG L C, WANG Y L, et al. Preoperative volumetric modulated arc therapy and helical tomotherapy for rectal cancer: a dosimetric study [J]. Academic Journal of PLA Postgraduate Medical School, 2014, 35(2): 146-149.

（编辑：薛泽玲）

（上接第160页）

[10] ZHANG X, LI X, QUAN E M, et al. A methodology for automatic intensity-modulated radiation treatment planning for lung cancer[J]. Phys Med Biol, 2011, 56(13): 3873-3893.

[11] WU B, RICCHETTI F, SANGUINETI G, et al. Patient geometry-driven information retrieval for IMRT treatment plan quality control[J]. Med Phys, 2009, 36(12): 5497-5505.

[12] MATHAYOMCHAN B. Multiobjective approach to morphological based radiation treatment planning planning[D]. Cleveland: Case Mestern Reserve University, 2006.

[13] PETIT S F, WU B, KAZHDAN M, et al. Increased organ sparing using shape- based treatment plan optimization for intensity modulated radiation therapy of pancreatic adenocarcinoma [J]. Radiother Oncol, 2012, 102(1): 38-44.

[14] LIAN J, YUAN L L, GE Y R, et al. Modeling the dosimetry of organ-at-risk in head and neck IMRT planning: an intertechnique and interinstitutional study[J]. Med Phys, 2013, 40(40): 121704.

[15] GOOD D, LO J, LEE W R, et al. A knowledge-based approach to improving and homogenizing intensity modulated radiation therapy planning quality among treatment centers: an example application to prostate cancer planning [J]. Int J Radiat Oncol Biol Phys, 2013, 87(1): 176-181.

[16] NWANKWO O, MEKDASH H, SIHONO D S, et al. Knowled-based radiation therapy (KBRT) treatment planning *versus* planning by experts: validation of a KBRT algorithm for prostate cancer treatment planning[J]. Radiat Oncol, 2015, 10(1): 1-5.

[17] APPENZOLLER L, TAN J, YANG D, et al. Efficient method to train pDVH models with plan quality variation present in training cohort[J]. Radial Oncol, 2013, 87(2): 623-624.

[18] 李润箫, 迟子锋, 曹彦坤, 等. 直肠癌静态调强与容积旋转调强放疗计划的剂量学对比研究[J]. 中华放射医学与防护杂志, 2015, 35(2):123-127.
LI R X, CHI Z F, CAO Y K, et al. Dosimetric comparison of the VMAT and IMRT planning in rectal carcinoma[J]. Chinese Journal of Radiological Medicine and Protection, 2015, 35(2): 123-127.

（编辑：薛泽玲）