·论　著·

三种全乳同步瘤床加量调强放疗计划的比较

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［**摘要**］ **背景与目的：**目前保乳手术+术后放疗已成为早期乳腺癌标准治疗模式。采用3种不同适形调强放疗技术制定早期乳腺癌保乳术后全乳同步瘤床加量的放疗计划，并对3种放疗计划的肿瘤靶区、危及器官剂量学参数等方面进行比较。**方法：**随机选取上海交通大学医学院附属第九人民医院黄浦分院放疗科2018年度收治的女性乳腺癌保乳术后患者50例，左、右侧乳腺癌患者各25例。分别采用正向调强、逆向调强、容积调强等3种调强治疗方法制定全乳同步瘤床加量放疗计划。比较3种放疗计划的靶区适形度（conformity index，CI）与均匀度（homogeneity index，HI）；危及器官的剂量学参数，包括同侧肺（V_5、V_{20}、V_{30}）、心脏（D_{mean}、左乳癌V_{25}、右乳癌V_{15}）、对侧乳腺（D_2、D_{mean}）；单次治疗的总跳数（minute，MU）及出束时间，并进一步分析乳房体积大小对放疗计划的影响。**结果：**正向调强、逆向调强与容积调强放疗计划的全乳靶区CI分别为0.69±0.09、0.86±0.06和0.79±0.07（两两比较P<0.001），瘤床靶区CI分别为0.71±0.15、0.79±0.15和0.80±0.12（两两比较P=0.007、P<0.001和P=0.624），全乳靶区HI分别为0.17±0.03、0.13±0.03和0.18±0.03（两两比较P<0.001），瘤床靶区HI分别为0.17±0.05、0.07±0.01和0.10±0.02（两两比较P<0.001）。同侧肺V_5为56.08±7.24、46.08±5.48和57.82±6.64（两两比较P<0.001、P=0.079、P<0.001），V_{20}为27.96±2.57、20.28±2.13和23.44±2.71（两两比较P<0.001、P=0.025、P<0.001），V_{30}为22.34±2.20、15.40±2.37和16.42±2.82（两两比较P<0.001、P=0.006、P=0.012）。左乳癌心脏D_{mean}为775.48±113.23、584.20±223.04和634.24±174.38（两两比较P<0.001、P<0.001、P=0.045），右乳癌心脏D_{mean}为209.32±84.60、125.56±41.65和200.80±49.74（两两比较P<0.001、P=0.524、P<0.001），左乳癌心脏V_{25}为8.20±1.73、5.02±1.38和6.65±1.56（两两比较P<0.001、P<0.001、P=0.037），右乳癌心脏V_{15}均为0值不做比较。对侧乳腺的D_{mean}为288.05±105.14、108.25±56.47和123.59±73.79（两两比较P<0.001、P<0.001、P=0.023）。单次治疗MU为285.74±17.73、1463.94±227.74和445.50±98.22（两两比较P<0.001），出束时间为205.12±20.68、343.26±37.59和138.06±13.53（两两比较P<0.001）。50例患者以患侧乳房体积平均值764.89 mL为界分成两组，乳房小体积组3种放疗计划的靶区CI、HI以及单次MU与出束时间优于乳房大体积组，而在正常器官剂量学方面两组间差异无统计学意义。**结论：**逆向调强与容积调强在靶区剂量学参数及危及器官的保护方面优于正向调强计划。其中逆向调强计划稍优于容积调强，推荐用于耐受较好、有长期生存预期的中、青年患者；而容积调强计划的单次MU更少，出束时间更短，建议老年、乳房体积较大的患者采用。

［**关键词**］早期乳腺癌；同步瘤床加量；调强放疗
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Comparison of three types of intensity-modulated radiotherapy plans for adjuvant whole breast and simultaneous tumor bed boost radiotherapy

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［**Abstract**］ **Background and purpose:** Breast-conserving surgery (BCS) plus post-operative radiation therapy has become the standard of care for early stage breast cancer. This study aimed to design whole breast and simultaneous tumor bed boost radiation therapy plans by adopting 3 different types of intensity-modulated radiation therapy (IMRT) techniques, and to compare the dosimetric parameters involving target volumes, organs at risk (OARs) and other aspects of the three IMRT plans. **Methods:** Fifty female patients with early stage breast cancer (25 left and 25 right, respectively) treated with BCS during the year of 2018 in Department of Radiation Oncology, Shanghai Jiao Tong University Medical School Affiliated Ninth People's Hospital Huangpu

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Branch, were randomly selected. Adjuvant whole breast and simultaneous tumor bed boost radiation therapy plans were designed by adopting forward-planned IMRT, reverse-planned IMRT and volumetric modulated arc therapy (VMAT) techniques. Conformity index (CI) and homogeneity index (HI) of target volumes, dosimetric parameters of OARs, including ipsilateral lung (V_5, V_{20}, V_{30}), heart (D_{mean}, V_{25} for left breast cancer, V_{15}), contralateral breast (D_2, D_{mean}), single fraction minute (MU) and beam-out time of the three IMRT plans were compared, respectively. Further analysis was made to identify the effect of breast volume on IMRT plans. **Results:** CI of forward-planned IMRT, reverse-planned IMRT and VMAT for whole breast target volume were 0.69±0.09, 0.86±0.06, 0.79±0.07, respectively (pairwise comparison P<0.001). CI for tumor bed target volume were 0.71±0.15, 0.79±0.15 and 0.80±0.12, respectively (pairwise comparison, P=0007, P<0.001, P=0.624, respectively). HI of the three plans for whole breast target volume were 0.17±0.03, 0.13±0.03 and 0.18±0.03, respectively (pairwise comparison, P<0.001). HI for tumor bed target volume were 0.17±0.05, 0.07±0.01 and 0.10±0.02, respectively (pairwise comparison, P<0.001). Ipsilateral lung V_5 was 56.08±7.24, 46.08±5.48 and 57.82±6.64, respectively (pairwise comparison, P<0.001, P=0.079, P<0.001, respectively). V_{20} was 27.96±2.57, 20.28±2.13 and 23.44±2.71, respectively (pairwise comparison, P<0.001, P=0.025, P<0.001, respectively). V_{30} was 22.34±2.20, 15.40±2.37 and 16.42±2.82, respectively (pairwise comparison, P<0.001, P=0.006, P<0.012, respectively). Heart D_{mean} for left breast cancer was 775.48±113.23, 584.20±223.04 and 634.24±174.38, respectively (pairwise comparison, P<0.001, P<0.001, P=0.045, respectively). Heart D_{mean} for right breast cancer was 209.32±84.60, 125.56±41.65 and 200.80±49.74, respectively (pairwise comparison, P<0.001, P=0.524, P<0.001, respectively). Heart V_{25} for left breast cancer was 8.20±1.73, 5.02±1.38 and 6.65±1.56, respectively (pairwise comparison, P<0.001, P<0.001, P=0.037, respectively). Heart V_{15} for right breast cancer was 0 for all, and no further comparison was made. Contralateral breast D_{mean} was 288.05±105.14, 108.25±56.47 and 123.59±73.79, respectively (pairwise comparison, P<0.001, P<0.001, P=0.023, respectively). Single fraction MU was 285.74±17.73, 1463.94±227.74 and 445.50±98.22, respectively (pairwise comparison, P<0.001). Beam-out time was 205.12±20.68, 343.26±37.59 and 138.06±13.53, respectively (pairwise comparison, P<0.001). A total of 50 patients were divided into small/large breast volume groups according to the mean breast volume (764.89 mL). Better dosimetric parameters of target volumes, fewer single fraction MUs and shorter beam-out time were found in small volume group. No statistical difference in OARs' dosimetric parameters was found in the two groups. **Conclusion:** Reverse-planned IMRT and VMAT were better than forward-planned IMRT in the aspects of target volumes' dosimetric parameters and protection of OARs. Reverse-planned IMRT was slightly superior to VMAT, and was recommended for younger patients with better tolerability and longer life expectancy. VMAT had both fewer single fraction MUs and shorter beam-out time, and was preferable for patients with older age and larger breast volume.

［**Key words**］ Early stage breast cancer; Simultaneous tumor bed boost; Intensity-modulated radiotherapy

目前保乳手术+术后放疗已成为早期乳腺癌的标准治疗模式[1-3]。保乳术后放疗靶区包括患侧全乳及术后瘤床。全乳放疗同步瘤床推量对比续贯瘤床推量，可缩短总的放疗疗程时间，降低正常组织（尤其是皮肤）的受照射剂量[4-5]，降低治疗总费用[6]，提高患者治疗的依从性[7]。此外，各种调强放疗技术也越来越多地应用于保乳术后的放疗中，其优势包括更加均匀的靶区剂量分布与更低的正常组织受照射剂量[8]，可能有利于提高早期保乳术后患者远期的生活质量。本研究旨在通过对采用3种不同的适形调强放疗（intensity-modulated radiation therapy，IMRT）技术设计的早期乳腺癌保乳术后放疗计划相关参数进行比较，分析3种IMRT技术适合应用的患者人群。

1 资料和方法

1.1 病例选取

随机选取上海交通大学医学院附属第九人民医院黄浦分院放疗科2018年度收治的女性早期乳腺癌保乳术后患者50例，左、右侧乳腺癌各25例。年龄30~79岁，采用美国东部肿瘤协作组（Eastern Cooperative Oncology Group，ECOG）PS评分为0~1分，术后分期按美国癌症联合会（American Joint Committee on Cancer，AJCC）第8版分期标准分为$T_{1-2}N_0M_0$期，其中腋窝淋巴结的手术方式包括前哨淋巴结活检22例，腋窝淋巴结清扫28例。

1.2 CT模拟定位

所有患者均借助体位固定装置Civco

P109444-PSR-2C-30臂托（arm support）按治疗体位固定，并采用荷兰飞利浦公司Brilliance 16排大孔径CT模拟定位机扫描定位。扫描范围头端至舌骨体平面，尾端至上腹部，层厚5 mm连续扫描，将图像传输到Eclipse 11治疗计划系统。

1.3 靶区与正常器官勾画

放疗靶区依据国际辐射学单位委员会（International Commission Radiological Units，ICRU）第83号报告的定义，包括临床靶区（clinical target volume，CTV)及计划靶区（planning target volume，PTV）。

全乳CTV按照美国肿瘤放疗组（Radiation Therapy Oncology Group，RTOG）乳腺癌放疗靶区勾画图谱介绍的范围进行勾画[9]，瘤床CTV按照术中留置的钛夹范围外扩1~2 cm进行勾画，前后界同全乳CTV。PTV是在CTV基础上向前、后、内、外界各外扩7 mm，上、下界各外扩1 cm，其中前界皮肤内收5 mm，后界避开患侧肺。正常器官包括双侧全肺和心脏，双侧肺分别勾画。

1.4 处方剂量、危及器官限量与治疗计划的设计

全乳靶区处方剂量50 Gy/25次/5周，瘤床靶区同步推量至60 Gy/25次/5周，要求95%的处方剂量覆盖100%的PTV。正常器官限量：同侧肺$V_5<75\%$，$V_{20}<30\%$，$V_{30}<20\%$；全肺$V_5<45\%$，$V_{15}<30\%$；心脏：左乳癌$V_{25}<10\%$，右乳癌$V_{15}<5\%$；对侧乳房：$D_2<10$ Gy，$D_{mean}<5$ Gy[10-11]。所有计划均采用6 MV X射线，均需满足以上剂量要求。

1.4.1 正向IMRT

全乳靶区采用常规切线野入射角度为主照射野角度，并在内外切线方向设置2~3个子野，人工调整主野及子野的剂量权重与跳数（minute，MU）以实现与靶区适形的高剂量区。如靶区局部剂量不足，考虑再予1~2个子野进行剂量补充。针对瘤床靶区增设2~3个射野，实现同步推量。

1.4.2 逆向IMRT

采用常规切线入射角度设置7~8个照射野，剂量率为400 MU/min。根据靶区形状体积选取适当的计划中心，以右侧乳腺癌为例：靶区长度的中点，腋中线附近，胸骨靠患侧6~8 cm，分别确定X、Y、Z坐标，给予40°至60°的射野角度，对侧射野角度为240°至220°。同时在射束方向视图（beam eye view，BEV）下调整小机头角度，使射野的长轴与肺部轮廓成切线状态，增加调制能力。逆向调强的计算过程是给予靶区要求达到的处方剂量，过程由计算机自动计算，在目标函数中输入最大照射剂量与最小照射剂量进行逆向优化。根据优化的计算结果换算每个射野的剂量权重和MU。

1.4.3 容积-旋转调强计划（volumetric modulated arc therapy，VMAT）

采用双弧照射技术，在常规切野角度的±30°范围内顺时针/逆时针旋转照射。最大剂量率600 MU/min。剂量的计算采用各项异性解析（anisotropic analytical algorithm，AAA）算法，并通过剂量成形结构（dose shaping structure，DSS）技术对剂量的冷热点进行优化。

1.5 计划比较

1.5.1 靶区剂量统计

包括全乳与瘤床PTV的剂量适形度（conformity index，CI）与均匀度（homogeneity index，HI）。

$$CI=_{Vt,ref}/V_t\times V_{t,ref}/V_{ref}$$

其中V_t表示靶区体积，$V_{t,ref}$表示靶区内处方剂量等剂量曲线所包绕的靶区体积，V_{ref}表示处方剂量等剂量曲线所包绕的全部体积。CI的范围为0~1，越接近1，表明靶区剂量CI越好。

$$HI=D_2-D_{98}/D_p\times100\%$$

其中D_2与D_{98}分别表示2%与98%的PTV体积所对应的的照射剂量，即分别代表了靶区最大与最小剂量。D_p表示处方剂量。HI的范围为0~1，越接近于0，表明靶区剂量分布越均匀。

1.5.2 正常器官剂量统计

同侧肺V_5、V_{20}、V_{30}，即受到5、20和30 Gy剂量照射的同侧肺百分体积；心脏的平均剂量（D_{mean}）与V_{25}（左乳癌）/V_{15}（右乳癌）；对侧乳腺的D_2与D_{mean}。

1.5.3 单次MU与出束时间

计算3种计划的单次放疗各照射野的MU总

和，并记录每位入组患者3种不同放疗计划的实际出束时间（beam-out time），精确到秒。

1.6 统计学处理

不同计划中每项参数的比较采用t检验，列表记录采用$\bar{x}\pm s$的形式。采用SPSS 19.0统计软件对数据进行分析，$P<0.05$为差异有统计学意义。

2 结 果

2.1 靶区的剂量参数

全乳靶区CI方面，逆向IMRT计划最优，VMAT计划次之，正向IMRT最低，两两比较结果差异均有统计学意义；瘤床靶区CI方面，逆向IMRT与VMAT计划相比无显著差异，但均优于正向IMRT计划（表1）。

全乳靶区剂量HI方面，总体比较与两两比较结果差异均有统计学意义，以逆向IMRT计划为最优，正向IMRT计划次之，VMAT计划则最差；瘤床靶区剂量HI方面，以逆向IMRT计划为最优，VMAT次之，正向IMRT计划最差。

图1所示为1例典型病例的3种调强计划的靶区剂量–体积直方图。全乳与瘤床靶区的95%处方剂量云图见图2~4。

表 1 全乳靶区与瘤床靶区的CI与HI比较

Tab. 1 Comparison of CI and HI for whole breast and tumor bed target volumes

Type of IMRT	Whole breast target volume CI	*P* value	Tumor bed CI	*P* value	Whole breast target volume HI	*P* value	Tumor bed HI	*P* value
Forward-planned IMRT	0.69 ± 0.09	<0.001*	0.71 ± 0.15	0.007*	0.17 ± 0.03	<0.001*	0.17 ± 0.05	<0.001*
Reverse-planned IMRT	0.86 ± 0.06	<0.001#	0.79 ± 0.15	<0.001#	0.13 ± 0.03	0.001#	0.07 ± 0.01	<0.001#
VMAT	0.79 ± 0.07	0.001△	0.80 ± 0.12	0.624△	0.18 ± 0.03	<0.001△	0.10 ± 0.02	<0.001△

*: Forward-planned IMRT *vs* reversed-planned IMRT; #: Forward-planned IMRT *vs* VMAT; △: Reversed-planned IMRT *vs* VMAT

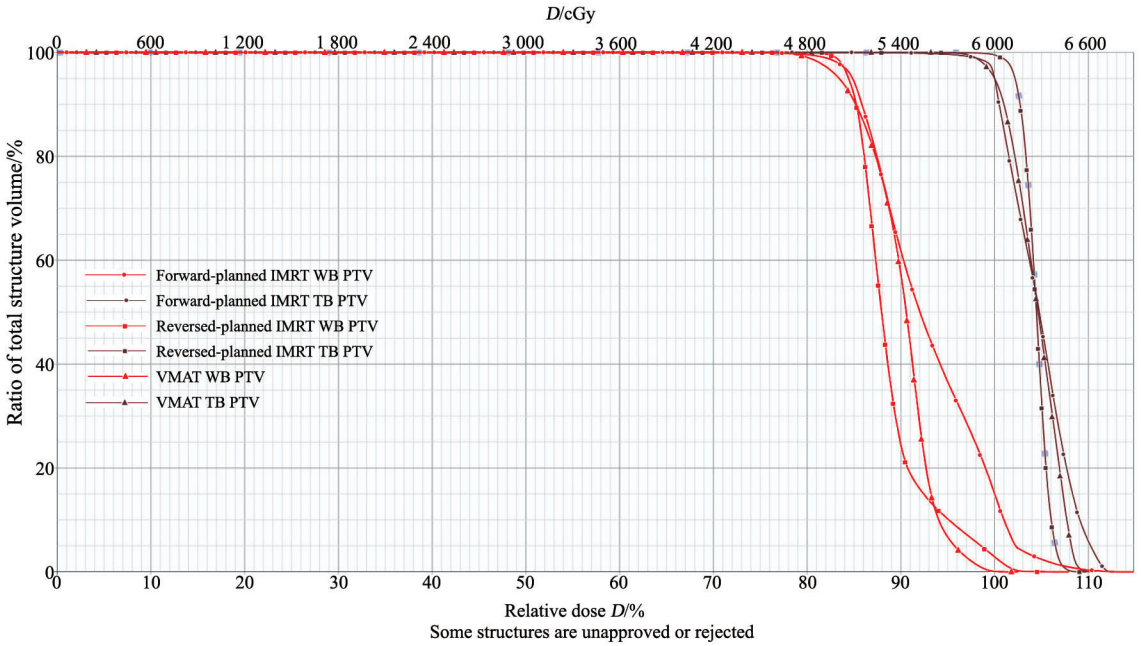

图 1 3种计划全乳与瘤床PTV的剂量–容积直方图

Fig. 1 Comparison of whole breast and tumor bed PTV dose-volume histograms for 3 types of plan

WB: Whole breast; TB: Tumor bed; PTV: Planned target volume; IMRT: Intensity-modulated radiation therapy; VMAT: Volumetric modulated arc therapy

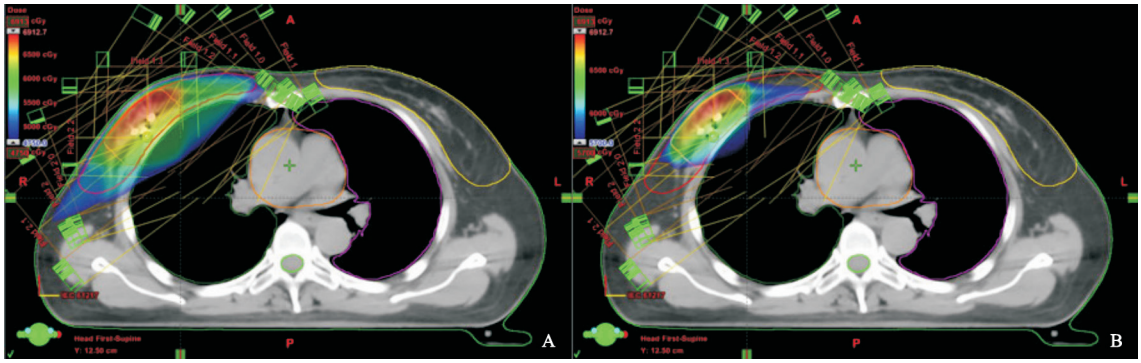

图 2　正向调强计划的全乳（A）与瘤床（B）靶区剂量云图

Fig. 2　Dose colour washout pictures of whole breast (A) and tumor bed (B) PTV for forward-planned IMRT

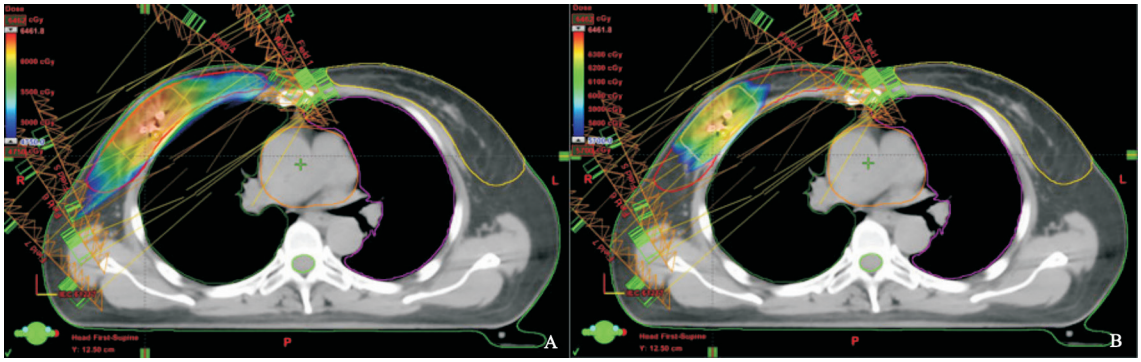

图 3　逆向调强计划的全乳（A）与瘤床（B）靶区剂量云图

Fig. 3　Dose colour washout pictures of whole breast (A) and tumor bed (B) PTV for reverse-planned IMRT

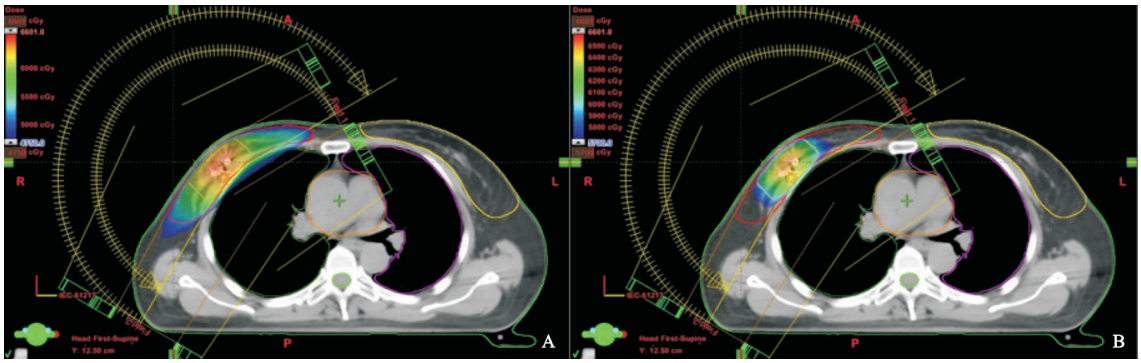

图 4　VMAT计划的全乳（A）与瘤床（B）靶区剂量云图

Fig. 4　Dose color washout pictures of whole breast (A) and tumor bed (B) PTV for VMAT

2.2　正常组织的剂量参数

2.2.1　同侧肺

低剂量照射体积V_5，以逆向IMRT计划较低，VMAT计划与正向IMRT之间的差异无统计学意义；V_{20}与V_{30}的结果相似，均以逆向IRMT计划最低，VMAT次之，正向IMRT最高（表2）。

2.2.2　心脏

表3比较了心脏剂量参数，左/右乳癌心脏平均剂量（D_{mean}）与左乳癌的心脏V_{25}的比较结果一致，均以逆向IMRT和VMAT计划的较低，正向IMRT计划较高。

2.2.3　对侧乳腺

对侧乳腺平均剂量（D_{mean}）以逆向IMRT计划为最低，VMAT计划次之，正向IMRT计划最高；对侧乳腺最大剂量（D_2）以VMAT计划为最低，逆向IMRT计划次之，正向IMRT计划最高（表4）。

2.3　单次MU与出束时间比较

表5比较了单次治疗的MU和出束时间。单次治疗的MU以正向IMRT为最低，VMAT计划次

表 2 同侧肺的剂量学参数比较

Tab. 2 Dosimetric comparison for ipsilateral lung

Type of IMRT	V_5/%	*P* value	V_{20}/%	*P* value	V_{30}/%	*P* value
Forward-planned IMRT	56.08 ± 7.24	<0.001*	27.96 ± 2.57	<0.001*	22.34 ± 2.20	<0.001*
Reverse-planned IMRT	46.08 ± 5.48	0.079#	20.28 ± 2.13	0.025#	15.40 ± 2.37	0.006#
VMAT	57.82 ± 6.64	<0.001△	23.44 ± 2.71	<0.001△	16.42 ± 2.82	0.012△

*: Forward-planned IMRT *vs* reversed-planned IMRT; #: Forward-planned IMRT *vs* VMAT; △: Reversed-planned IMRT *vs* VMAT

表 3 心脏的剂量学参数比较

Tab. 3 Dosimetric comparison for heart

Type of IMRT	Left BC D_{mean} *D*/cGy	*P* value	Left BC V_{25}/%	*P* value	Right BC D_{mean} *D*/cGy	*P* value	Right BC V_{15}/%	*P* value
Forward-planned IMRT	775.48 ± 113.23	<0.001*	8.20 ± 1.73	<0.001*	209.32 ± 84.60	<0.001*	0	NS*
Reverse-planned IMRT	584.20 ± 223.04	<0.001#	5.02 ± 1.38	<0.001#	125.56 ± 41.65	0.524#	0	NS#
VMAT	634.24 ± 174.38	0.045△	6.65 ± 1.56	0.037△	200.80 ± 49.74	<0.001△	0	NS△

*: Forward-planned IMRT *vs* reversed-planned IMRT; #: Forward-planned IMRT *vs* VMAT;△: Reversed-planned IMRT *vs* VMAT; NS: No significance; BC: Breast cancer

表 4 对侧乳房的剂量学参数比较

Tab. 4 Dosimetric comparison for contralateral breast

Type of IMRT	D_{mean} *D*/cGy	*P* value	D_2 *D*/cGy	*P* value
Forward-planned IMRT	288.05 ± 105.14	<0.001*	827.96 ± 162.57	<0.001*
Reverse-planned IMRT	108.25 ± 56.47	<0.001#	684.42 ± 125.76	<0.001#
VMAT	123.59 ± 73.79	0.023△	607.25 ± 102.29	0.042△

*: Forward-planned IMRT *vs* reversed-planned IMRT; #: Forward-planned IMRT *vs* VMAT;△: Reversed-planned IMRT *vs* VMAT

表 5 单次MU与出束时间的比较

Tab. 5 Comparison of single fraction MU and beam-out time

Type of IMRT	Single fraction MU	*P* value	Beam-out time *t*/s	*P* value
Forward-planned IMRT	285.74 ± 17.73	<0.001*	205.12 ± 20.68	<0.001*
Reverse-planned IMRT	1 463.94 ± 227.74	<0.001#	343.26 ± 37.59	<0.001#
VMAT	445.50 ± 98.22	<0.001△	138.06 ± 13.53	<0.001△

*: Forward-planned IMRT *vs* reversed-planned IMRT; #: Forward-planned IMRT *vs* VMAT; △: Reversed-planned IMRT *vs* VMAT

之，逆向IMRT计划最高；单次出束时间的比较结果：VMAT计划最短，正向IMRT计划次之，逆向IMRT计划最长。

2.4 乳房体积对靶区及正常组织剂量的影响

50例患者以全乳PTV平均值（764.89 mL）为界限分为乳房小体积组与乳房大体积组，每组各25例。

不同乳房体积的正向IMRT/VMAT计划全乳与瘤床靶区的剂量HI、逆向IMRT全乳靶区的剂量HI差异均有统计学意义；正/逆向IMRT的单次MU、逆向IMRT单次出束时间均因乳房体积增大而增加（表6）。

表 6　大/小全乳容积的靶区与危及器官的剂量学参数比较

Tab. 6　Dosimetric comparison of target volume and organs at risk between large/small breast volume

Parameter	Small breast volume	Large breast volume	*P* value
Forward-planned IMRT WB-TV CI	0.69 ± 0.08	0.69 ± 0.09	0.033
Forward-planned IMRT TB-TV CI	0.71 ± 0.07	0.70 ± 0.12	0.290
Forward-planned IMRT WB-TV HI	0.18 ± 0.02	0.18 ± 0.03	<0.001
Forward-planned IMRT TB-TV HI	0.14 ± 0.03	0.20 ± 0.06	<0.001
Reverse-planned IMRT WB-TV CI	0.84 ± 0.07	0.89 ± 0.05	0.005
Reverse –planned IMRT TB-TV CI	0.83 ± 0.09	0.75 ± 0.19	0.061
Reverse –planned IMRT WB-TV HI	0.12 ± 0.02	0.15 ± 0.02	<0.001
Reverse –planned IMRT TB-TV HI	0.07 ± 0.01	0.07 ± 0.01	0.202
VMAT WB-TV CI	0.77 ± 0.07	0.80 ± 0.06	0.091
VMAT TB-TV CI	0.81 ± 0.12	0.80 ± 0.12	0.679
VMAT WB-TV HI	0.17 ± 0.03	0.20 ± 0.03	<0.001
VMAT TB-TV HI	0.09 ± 0.01	0.10 ± 0.02	0.012
Forward-planned IMRT I/L V_5/%	56.12 ± 5.93	56.04 ± 8.56	0.972
Forward-planned IMRT I/L V_{20}/%	27.92 ± 2.23	28.00 ± 2.95	0.917
Forward-planned IMRT I/L V_{30}/%	22.35 ± 1.93	22.33 ± 2.50	0.984
Reverse –planned IMRT I/L V_5/%	44.65 ± 3.73	47.63 ± 6.63	0.061
Reverse –planned IMRT I/L V_{20}/%	20.42 ± 1.82	20.13 ± 2.46	0.626
Reverse –planned IMRT I/L V_{30}/%	15.77 ± 2.14	15.00 ± 2.59	0.256
VMAT I/L V_5/%	57.96 ± 6.46	57.67 ± 6.96	0.877
VMAT I/L V_{20}/%	23.19 ± 2.23	23.71 ± 3.20	0.508
VMAT I/L V_{30}/%	16.15 ± 1.91	16.71 ± 3.57	0.503
Forward-planned IMRT heart $D_{mean}$of left BC D/cGy	770.33 ± 180.81	778.38 ± 102.55	0.888
Reverse –planned IMRT heart $D_{mean}$of left BC D/cGy	510.44 ± 174.78	625.69 ± 241.26	0.222
VMAT heart D_{mean} of left BC D/cGy	591.22 ± 163.45	658.44 ± 180.75	0.366
Forward-planned IMRT heart V_{25} of left BC/%	8.11 ± 1.83	8.26 ± 1.64	0.864
Reverse -planned IMRT heart V_{25} of left BC/%	4.65 ± 1.25	5.23 ± 1.44	0.565
VMAT heart V_{25} of left BC/%	6.37 ± 1.38	6.69 ± 1.58	0.763
Forward –planned IMRT contralateral breast D_{mean} D/cGy	276.33 ± 103.26	289.65 ± 113.42	0.364
Reverse–planned IMRT contralateral breast D_{mean} D/cGy	106.73 ± 54.38	112.36 ± 64.87	0.412
VMAT contralateral breast D_{mean} D/cGy	117.38 ± 71.22	127.53 ± 82.51	0.073
Forward –planned IMRT contralateral breast D_2 D/cGy	795.29 ± 132.77	834.08 ± 171.26	0.149
Reverse–planned IMRT contralateral breast D_2 D/cGy	633.56 ± 107.25	68.42 ± 184.06	0.283
VMAT contralateral breast D_2 D/cGy	585.22 ± 89.06	636.03 ± 117.28	0.355
Forward-planned IMRT single fraction MU	279.77 ± 11.54	292.21 ± 21.01	0.015
Forward-planned IMRT beam-out time t/s	202.50 ± 16.76	207.96 ± 24.28	0.356
Reverse–planned IMRT single fraction MU	1 348.27 ± 119.02	1 589.25 ± 252.16	<0.001
Reverse–planned IMRT beam-out time t/s	321.77 ± 30.29	366.54 ± 30.44	<0.001
VMAT single fraction MU	455.19 ± 98.54	435.00 ± 98.88	0.473
VMAT beam-out time t/s	139.46 ± 12.87	139.54 ± 14.34	0.452

WB: Whole breast; TB: Tumor bed; TV: Target volume; I/L: Ipsilateral lung; BC: Breast cancer

3 讨 论

2000年Evans等[12]报道了静态多野IMRT在乳腺切线照射治疗中的应用。该研究发现IMRT能够提高肿瘤靶区剂量CI与HI、降低正常组织的受照射剂量，这些剂量学方面的改变与临床上实现提高肿瘤局控率、改善患者生存以及生活质量的目标密切相关。随着放疗精确化技术诸如野中野正向调强、逆向调强、容积调强等逐步应用于乳腺癌的治疗，相关治疗计划的剂量学特点与疗效的研究也在国内外广泛开展[13-15]。VMAT近两年也被用于多个部位肿瘤的研究[16-17]，但在乳腺癌临床治疗中并未得到广泛运用。

保乳术后辅助放疗中，瘤床区的加量问题一直是研究的热点。如研究瘤床加量的射线性质，用X线加量还是电子线加量；研究瘤床加量的时间，是全乳放疗时同期加量还是序贯加量。全乳放疗瘤床同期加量时，瘤床分割剂量为2.4 Gy，高于常规分割剂量2.0 Gy，属于大分割。细胞动力学研究显示，乳腺癌具有高于平均值的潜在倍增时间，适于大分割照射[18]，且采用大分割照射可获得较高的放射治疗比[19]。欧洲癌症研究治疗中心（European Organzation for Research and Treatment of Cancer，EORTC）对瘤床同期加量及非同期加量照射进行了临床对照研究，结果显示，瘤床区同期加量组相较于非同期加量组20年乳腺内复发率显著减低（9% *vs* 13%）[20]。瘤床区同期加量放疗相较于常规的序贯瘤床加量放疗而言，可显著缩短治疗的周期[21]。在剂量分布方面，可以通过治疗计划系统的优化改善瘤床区剂量分布的均匀性。在放射生物学方面，该技术提高了亚临床病灶区的单次剂量，具有更高的生物学效应[22]。因此，瘤床区同期加量放疗技术已逐渐成为保乳术后放射治疗的主流模式。

尽管2018年美国放射肿瘤学会（American Society for Radiation Oncology，ASTRO）更新了全乳大分割治疗的共识，消除了年龄、分期以及是否化疗等因素对大分割放疗应用的的影响[23]，然而，收费和患者的认知等因素限制着大分割放疗在国内的推广。

本研究采用全乳常规分割放疗与瘤床同步推量的方案，并用3种调强放疗技术设计放疗计划。研究结果显示，在全乳/瘤床靶区的CI与HI以及危及器官的剂量-体积参数方面，逆向IMRT、VMAT明显优于正向IMRT，其中逆向IMRT在大部分参数比较中的表现均体现出明显的优势，该结果与其他研究结果相符[24-25]。究其原因，逆向调强治疗计划系统中的逆向剂量参数优化功能可谓功不可没，而正向IMRT计划表现相对较差。本研究结果显示，VMAT及正向IMRT计划的单次MU与出束时间方面有优势，而逆向IMRT则劣势较明显，究其原因，可能与治疗过程中加速器持续出束被多叶光栅（multi-leaf collimator，MLC）动态滑窗屏蔽而造成了较多的无效MU有关。而VMAT尽管也有部分无效MU，但由于较高的剂量率以及连续的机架转动与MLC运动，缩短了单次治疗时间，提高了治疗效率。然而，由于照射角度的连续性，不可避免地增加了正常器官（尤其是心脏及双肺）低剂量照射容积。

本研究还显示，全乳靶区体积较大时靶区的HI较差，无论正向/逆向计划均无法克服靶区容积带来的影响。此外，较大的靶区体积增加了单次计划的总MU及出束时间，这在3种治疗计划中均有所体现。因此对于较大靶区体积的老年患者，建议采用VMAT治疗计划以缩短治疗时间并提高患者的治疗依从性，而对于靶区体积较小且需要更加强调正常器官剂量限制的年轻患者，可用逆向IMRT来实现更加符合治疗要求的剂量雕刻。

逆向计划（包括逆向IMRT与VMAT）无论在靶区的剂量学参数还是在正常组织的限量方面均优于正向IMRT。在两种逆向计划的比较方面，除了对侧乳腺最大照射剂量（D_2）以外，逆向IMRT的计划参数均略优于VMAT。因此，对于那些耐受较好、有长期生存预期的中、青年放疗患者推荐使用逆向IMRT治疗，而VMAT因单次MU更少，出束时间更短，建议老年、乳房体积较大的患者采用。

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