DOI:10.3969/j.issn.1005-202X.2020.07.004

医学放射物理

# CT-电子密度转换曲线误差对IMRT剂量计算结果的影响

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**【摘要】目的：**研究CT-相对电子密度转换曲线误差对调强放射治疗（IMRT）计划剂量计算结果的影响。**方法：**随机选取南方医科大学顺德医院IMRT治疗的宫颈癌患者10例，在Eclipse治疗计划系统中对IMRT计划引入CT-电子密度转换曲线误差（±0.5%、±1.0%、±1.5%、±2.0%和±3.0%），重新计算剂量分布，每例患者得到10个带有误差的新计划并与原计划进行比较。分析转换曲线误差对剂量计算结果的影响，包括靶区相关剂量参数、适形度指数（Conformal Index, CI）、均匀性指数（Homogeneity Index, HI）和脊髓、肾脏、小肠、膀胱、直肠等危及器官体积剂量参数。分析不同转换曲线误差和各剂量参数偏差值之间的关系。**结果：**转换曲线引入正误差时计划剂量参数降低，引入负误差时计划剂量参数升高，引入的误差越大剂量变化越大。当转换曲线误差为1.5%时，靶区平均覆盖率为94.73%±1.86%，误差继续增大，带来的影响超出临床可接受范围。CI和HI在不同误差的计划之间没有统计学意义（$P$>0.05）。不同转换曲线误差和各剂量参数偏差值之间存在显著性负相关性（$P$均<0.001），并利用Matlab得到不同转换曲线误差和各剂量参数偏差值之间的相关公式。**结论：**当转换曲线误差大于1.5%时，剂量偏差无法满足临床要求。计划系统建模时需建立正确的CT-相对电子密度转换曲线，对CT模拟机要定期QA，以保证治疗计划剂量计算的精度。

**【关键词】**CT-电子密度转换曲线；误差；调强放射治疗；剂量计算
**【中图分类号】**R312；R811.1　**【文献标志码】**A　**【文章编号】**1005-202X(2020)07-0816-06

## Effect of the error of CT-electron density conversion curve on IMRT dose calculation

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**Abstract: Objective** To investigate the effect of the error of CT-electron density conversion curve on the calculation of dose distribution of intensity-modulated radiotherapy (IMRT) plan. **Methods** Ten patients undergoing IMRT for cervical cancer in Shunde Hospital of Southern Medical University were enrolled. Different CT-electron density conversion curve errors (±0.5%, ±1.0%, ±1.5%, ±2.0% and ±3.0%) were introduced into IMRT plans in Eclipse treatment planning system for recalculating dose distribution and obtaining 10 new plans for every patient which were then compared with the original plan without conversion curve errors. The effect of conversion curve errors on the dose calculation was discussed by analyzing the related dosimetric parameters, conformity index, homogeneity index of target areas, and the volume-dose parameters of organs-at-risk such as spinal cord, kidney, small intestine, bladder, rectum and so on. The relationships between different conversion curve errors and the deviation value of each dosimetric parameter were analyzed. **Results** The dosimetric parameters were decreased when positive errors were introduced into IMRT plan while increased when negative errors were introduced. The greater the conversion curve error was, the greater the effects on dosimetric parameters were. When the conversion curve error was 1.5%, the average target coverage was 94.73%+1.86%; and the dosimetric effect coming from larger conversion curve errors (higher than 1.5%) was out of the acceptable range in clinic. No statistical difference was found among plans with different conversion curve errors in conformity index and homogeneity index ($P$>0.05). There were significant negative correlations between conversion curve errors and the deviation values of different dosimetric parameters (all $P$<0.001), and the corresponding correlation formulas were obtained by Matlab software. **Conclusion** With conversion curve error higher than 1.5%, the dosimetric deviation is out of the acceptable range and the dose distribution cannot meet the clinical requirements. An accurate CT-electron density conversion curve should be created when

**【收稿日期】**2019-12-08
**【基金项目】**广东省自然科学基金（2018A030310678）
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building treatment model by planning system, and the quality assurance of CT-sim should be performed regularly, thereby ensuring the accurate calculation of dose calculation of treatment plan.

**Keywords:** CT-electron density conversion curve; error; intensity-modulated radiotherapy; dose calculation

## 前 言

治疗计划系统（Treatment Planning System, TPS）进行剂量计算依赖于CT影像中所包含的相对电子密度信息，该密度信息利用CT值转换得到，这一转换通常视所使用的CT而定[1]。TPS剂量计算时，错误的CT/电子密度（CT-ED）关系会造成剂量计算错误。CT值的大小受CT扫描参数如管电压、管电流、层厚等以及扫描条件的影响，导致对应物质的相对电子密度误差[2]。本研究主要分析CT-ED转换曲线误差对宫颈癌患者调强放射治疗（IMRT）计划剂量造成的影响，建立正确的CT-ED转换曲线应该在临床工作中予以重视，以保证治疗计划剂量计算的精度。

## 1 材料与方法

### 1.1 主要设备和仪器

（1）CT扫描机：西门子SOMATOM Definition AS 20层螺旋大孔径CT，CT床附加碳素纤维平板床面；（2）模体：CIRS062电子密度模体；（3）TPS：瓦里安Eclipse治疗计划系统；（4）直线加速器：瓦里安Trilogy直线加速器，MLC 60对，中间40对叶片，每片宽度5 mm，两端各10对叶片，宽度1 cm。

### 1.2 病例选择

随机选取2018年11月~2019年1月在南方医科大学顺德医院放射治疗科进行IMRT治疗的宫颈癌患者10例进行回顾性研究。年龄38~75岁，平均年龄61岁，中位年龄61岁。计划选择腹部CT-ED转换曲线完成，扫描电压120 kV，电流35 mA，层厚3 mm。

### 1.3 IMRT计划设计及CT-ED转换曲线引入

处方剂量5 040 cGy，分28次完成照射。采用前3后2或前2后3布野，射野避开对肾脏、直肠等危及器官的照射。在TPS对转换曲线引入±0.5%、±1.0%、±1.5%、±2.0%和±3.0%的误差，重新计算剂量分布。每例患者得到10个新计划，与原计划进行剂量学比较。

### 1.4 评价指标

分别评价原计划和新计划靶区及危及器官的剂量体积参数，评价指标包括：处方剂量包绕靶区体积（$V_{Rx}$）、最大剂量（$D_{2\%}$）、最小剂量（$D_{98\%}$）、适形度指数（Conformity Index, CI）和均匀性指数（Homogeneity Index, HI）；危及器官包括脊髓的最大剂量（$D_{1\,cc}$）、小肠的最大剂量（$D_{1\,cc}$）、膀胱和直肠的体积剂量（$V_{45\,Gy}$），以及股骨头的体积剂量（$V_{30\,Gy}$）[3]。

### 1.5 统计学方法

从10例宫颈癌患者IMRT计划中分别得出靶区$V_{Rx}$、$D_{2\%}$、$D_{98\%}$与转换曲线误差的散点图；危及器官脊髓、小肠最大剂量$D_{1\,cc}$与转换曲线误差的散点图；膀胱和直肠的体积剂量$V_{45\,Gy}$与转换曲线误差的散点图；股骨头的体积剂量$V_{30\,Gy}$与转换曲线误差的散点图。通过Matlab软件对上述数据进行拟合，采用线性拟合、多项式拟合等方法，拟合出靶区及危及器官剂量参数偏差值（Δ）与转换曲线误差之间的相关公式。采用SPSS 21.0统计软件进行统计学分析，计量资料用均数±标准差表示，相关性进行Spearman分析，$P<0.05$为差异有统计学意义。

## 2 结 果

### 2.1 转换曲线误差对靶区剂量参数的影响

如表1所示，当转换曲线误差为正数时，即CT-ED转换曲线数值增大，$V_{Rx}$降低，当出现1.5%偏差时，计划靶区（PTV）的$V_{Rx}$为94.73%±1.86%，误差继续增大，带来的影响超出临床可接受范围。当转换曲线误差为负数时，$V_{Rx}$升高，引入误差越大，$V_{Rx}$值越大。如图1所示，Matlab拟合得到转换曲线误差与$\Delta V_{Rx}$之间的相关公式如下所示：

表1 转换曲线误差对处方剂量包绕靶区体积的影响（$\bar{x} \pm s$, %）

Tab.1 Effect of conversion curve errors on target coverage (*Mean±SD*, %)

| 项目 | 转换曲线误差 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 3.0% | 2.0% | 1.5% | 1.0% | 0.5% | 0% | -0.5% | -1.0% | -1.5% | -2.0% | -3.0% |
| 覆盖率 | 90.30±3.11 | 93.57±2.32 | 94.73±1.86 | 95.67±1.47 | 96.46±1.11 | 97.12±0.85 | 97.61±0.68 | 98.02±0.55 | 98.33±0.44 | 98.60±0.36 | 99.00±0.26 |

$$\Delta V_{Rx}: f(x) = -2.436 \times e^{0.407\,9x} + 2.425 \times e^{-0.015\,85x} \quad (1)$$

对于$D_{2\%}$、$D_{98\%}$，引入正转换曲线误差，数值降低，引入负转换曲线误差，数值升高，引入的转换曲线误

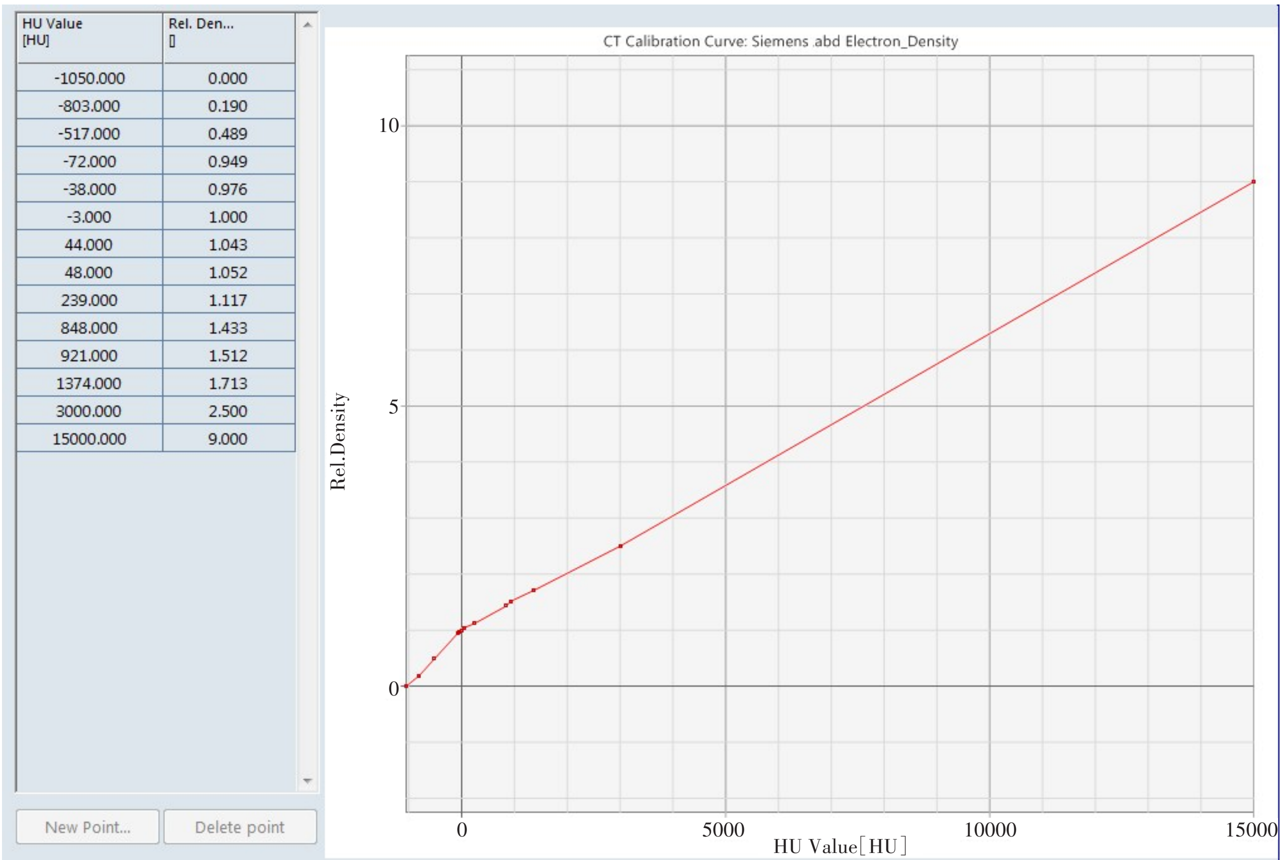



**图1 腹部CT-ED转换曲线**

**Fig.1 Abdominal CT-ED conversion curve**

差越大，$D_{2\%}$、$D_{98\%}$数值变化越大。如表2所示，$\Delta D_{2\%}$、$\Delta D_{98\%}$与转换曲线误差之间存在显著负相关性。如图2b和图2c所示，用Matlab得到转换曲线误差与$\Delta D_{2\%}$、$\Delta D_{98\%}$之间的相关公式：

$$\Delta D_{2\%}: f(x) = -16.87x + 0.8098 \quad (2)$$

$$\Delta D_{98\%}: f(x) = -16.68x - 0.07209 \quad (3)$$

CI、HI随转换曲线误差变化没有表现出明显规律，两者之间没有显著的相关性，如表2所示。图2a~图2i为10例患者IMRT计划靶区及危及器官剂量参数偏差值与转换曲线误差之间的散点图。

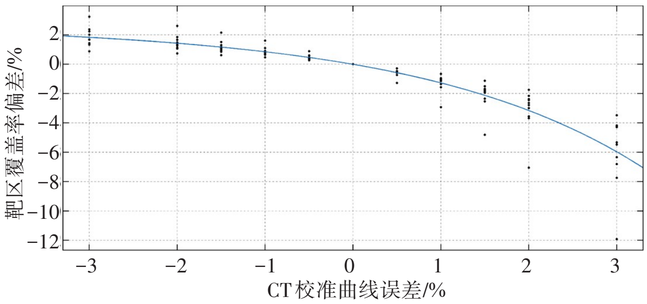
## 2.2 转换曲线误差对危及器官剂量参数的影响

脊髓-$D_{1\,cc}$、小肠-$D_{1\,cc}$、膀胱-$V_{45\,Gy}$、直肠-$V_{45\,Gy}$和股骨头-$V_{30\,Gy}$，在引入正转换曲线误差时，数值降低，引入负转换曲线误差时，数值升高，引入的转换曲线误

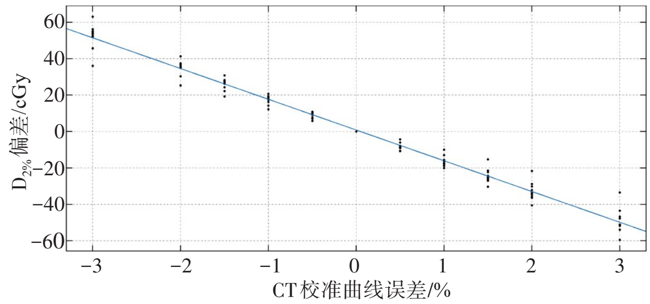
**表2 靶区及危及器官剂量参数偏差值与转换曲线误差之间的Spearman法相关分析**

**Tab.2 Spearman correlation analysis between the conversion curve errors and the deviation values of dosimetric parameters of target areas and organs-at-risk**

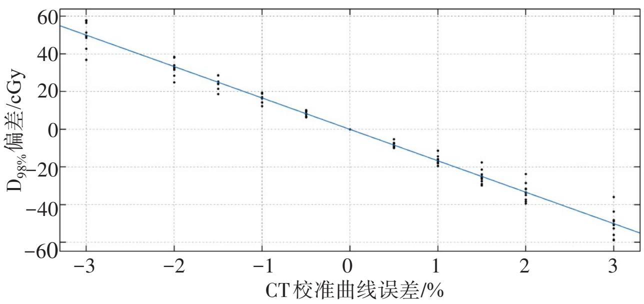
| 项目 | 相关性 | $r$值 | $P$值 |
|---|---|---|---|
| 转换曲线误差与ΔTC | 显著性负相关 | -0.947 | <0.01 |
| 转换曲线误差与$\Delta D_{2\%}$ | 显著性负相关 | -0.980 | <0.01 |
| 转换曲线误差与$\Delta D_{98\%}$ | 显著性负相关 | -0.981 | <0.01 |
| 转换曲线误差与$\Delta D_{1\,cc}$(小肠) | 显著性负相关 | -0.981 | <0.01 |
| 转换曲线误差与$\Delta D_{1\,cc}$(脊髓) | 显著性负相关 | -0.978 | <0.01 |
| 转换曲线误差与$\Delta V_{45\,Gy}$(膀胱) | 显著性负相关 | -0.931 | <0.01 |
| 转换曲线误差与$\Delta V_{30\,Gy}$(右侧股骨头) | 显著性负相关 | -0.805 | <0.01 |
| 转换曲线误差与$\Delta V_{30\,Gy}$(左侧股骨头) | 显著性负相关 | -0.833 | <0.01 |
| 转换曲线误差与$\Delta V_{45\,Gy}$(直肠) | 显著性负相关 | -0.930 | <0.01 |



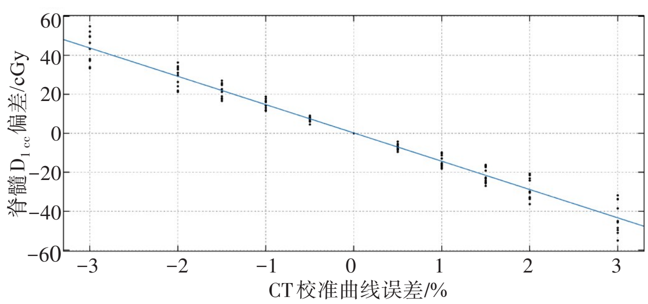

a：转换曲线误差与$\Delta V_{Rx}$之间的拟合曲线



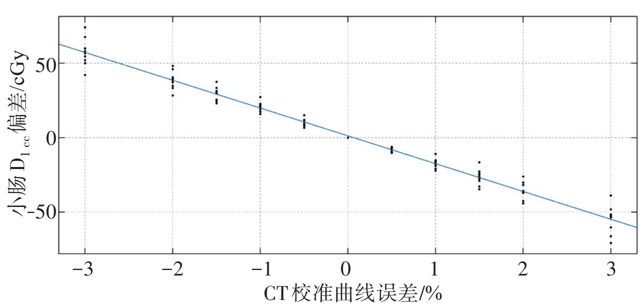

b：转换曲线误差与$\Delta D_{2\%}$之间的拟合曲线



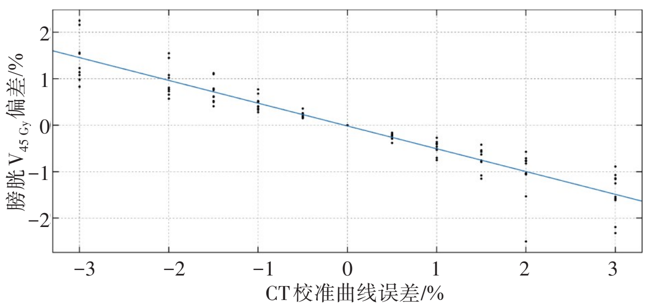

c：转换曲线误差与$\Delta V_{98\%}$之间的拟合曲线



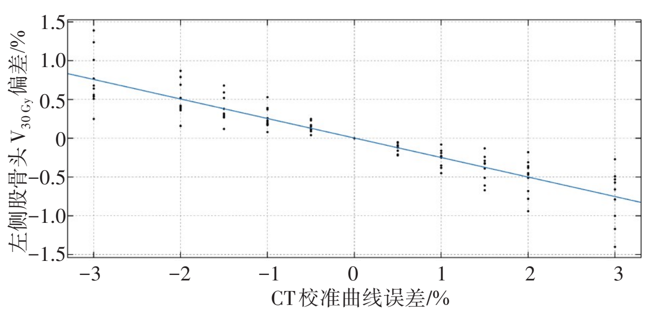

d：转换曲线误差与脊髓-$\Delta D_{1\ cc}$之间的拟合曲线



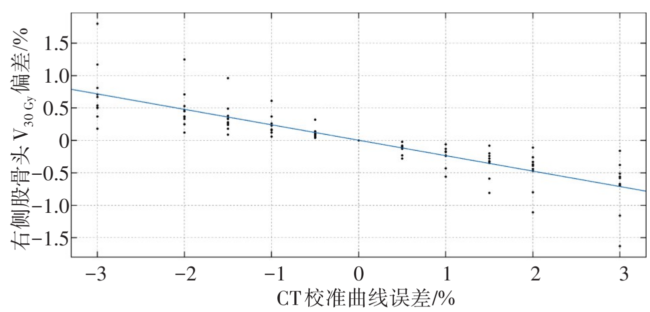

e：转换曲线误差与小肠-$\Delta D_{1\ cc}$之间的拟合曲线



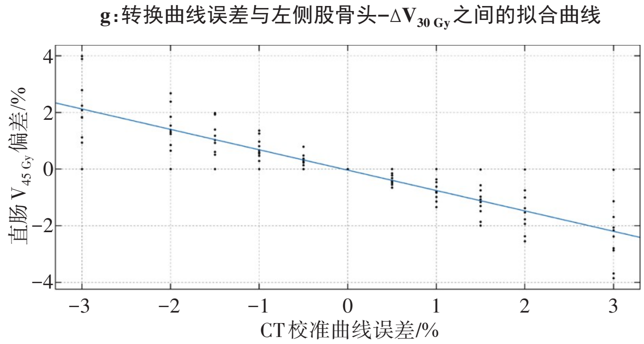

f：转换曲线误差与膀胱-$\Delta V_{45\ Gy}$之间的拟合曲线




g：转换曲线误差与左侧股骨头-$\Delta V_{30\ Gy}$之间的拟合曲线




h：转换曲线误差与右侧股骨头-$\Delta V_{30\ Gy}$之间的拟合曲线




i：转换曲线误差与直肠-$\Delta V_{45\ Gy}$之间的拟合曲线

**图2　10例患者IMRT计划靶区及危及器官剂量参数偏差值与转换曲线误差之间的散点图**

**Fig.2 Scatter plots between the conversion curve errors and the deviation values of dosimetric parameters of target areas and organs-at-risk in IMRT plans of 10 patients**

差越大，危及器官数值变化越大。如表2所示，危及器官剂量参数偏差值与转换曲线误差之间存在显著负相关性。图2a~图2i为用Matlab拟合得到的转换曲线误差与危及器官剂量参数偏差值之间的相关公式：

$$\text{脊髓-}\Delta D_{1\ cc}: f(x) = -14.52x + 0.177\ 5 \qquad (4)$$

小肠-$\Delta D_{1\,cc}$:$f(x)=-18.67x+1.221$ (5)

膀胱-$\Delta V_{45\,Gy}$:$f(x)=-0.490\,2x-0.016\,55$ (6)

左侧股骨头-$\Delta V_{30\,Gy}$:$f(x)=-0.251\,7x+0.003$ (7)

右侧股骨头-$\Delta V_{30\,Gy}$:$f(x)=-0.238\,2x+0.002\,218$ (8)

直肠-$\Delta V_{45\,Gy}$:$f(x)=-0.719\,5x-0.036$ (9)

## 3 讨论

为了确保放疗剂量的精确计算,需要保证计划系统CT-ED转换曲线的准确性。目前,有不少文献[4-12]对CT值和ED的关系进行了相应的研究。Zurl等[4]研究表明使用不同的CT扫描协议可以导致HU值高达20%的变化,导致系统平均剂量误差达到1.5%。李克等[13]研究了基于不同扫描部位采集的CT-ED转换曲线对放疗剂量的影响,结果表明在不同扫描部位下进行采集的CT-ED转换曲线对放疗剂量计算有一定影响,对于头部与胸部的肿瘤应该尽量选择对应扫描模式下的CT-ED转换曲线进行剂量计算,以保证治疗计划剂量计算的精度。

有研究表明CT定位条件和扫描参数可能导致CT值的改变,特别是扫描电压和CT定位床面的散射对CT值的影响较大[14]。此外,CT增强造影剂也会影响CT值从而影响剂量的计算,并且其浓度越高CT值则增加越多,导致剂量也会增高[15-16]。若体内有金属植入物,也会导致CT值产生较大的偏差,这种偏差包含金属植入物本身的CT值偏差以及金属导致的周围组织的CT值的偏差[17-18]。除此,若患者体内存在工人关节、心脏起搏器等外部植入物也可能导致CT值的变化,从而引起剂量计算的偏差。

由于客观因素,CT-ED转换曲线的误差无法完全避免。TPS剂量计算时,错误的CT-ED关系会造成剂量计算错误。研究表明,CT-ED转换曲线的误差有可能导致剂量计算结果相差3%以上[8, 19]。本研究侧重于分析CT-ED转换曲线误差对宫颈癌患者IMRT计划剂量造成的影响,拟合出靶区及危及器官剂量参数偏差值(Δ)与转换曲线误差之间的相关公式,以直观显示转换曲线误差对临床评价指标带来的影响。转换曲线引入正误差时计划剂量参数降低,引入负误差时计划剂量参数升高,引入的误差越大剂量变化越大。PTV的$V_{Rx}$与转换曲线误差显著性负相关,当出现1.5%偏差时,为94.73%±1.86%,误差继续增大,带来的影响超出临床可接受范围。

为确保CT-ED转换曲线的准确性,需要对CT进行定期质控。对此,AAPM TG 66号报告[20]详细描述了CT模拟机的质控规范,包括CT值精确性、电子密度和CT值的转换等均有相应检查频率和容差限值。不同厂家的CT模拟机性能参数都不完全一样,各个放疗中心应该根据自己设备的情况建立CT-ED转换曲线,并且考察可能影响CT密度值的因素,完善CT模拟机的QA标准。

总之,CT-ED转换曲线误差越大,导致剂量计算的误差也越大。在当今精确放疗的时代,需要定期对CT做相应的质控,保证CT-ED转换曲线的准确性,以保证放疗计划剂量计算的精度。

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（编辑：陈丽霞）