

# 基于不同参数估计方法获得的体素内不相干运动量化参数的可重复性研究

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**【摘要】目的:**利用不同参数估计方法,研究磁共振弥散加权成像(DWI)体素内不相干运动参数在正常肾脏皮质中的可重复性。**方法:**选取18例志愿者使用飞利浦Ingenia 3.0T核磁共振成像设备进行两次自由呼吸腹部肾脏多b值DWI。基于双指数模型,分别用非线性最小二乘拟合方法(NLLS)和贝叶斯估计方法(Bayes)从多b值DWI数据中计算体素内不相干运动的量化参数图(D、D\*、f)。从左右侧肾脏的皮质分别选取3个大小一致的感兴趣区,分别计算各个参数均值,并通过Bland-Altman评价方法比较两种方法获得的各个参数的可重复性。**结果:**Bayes方法计算的参数D、f和D\*在两次扫描间的变化系数分别为37.4%、30.0%和64.0%,NLLS方法计算获得的参数D、f和D\*在两次扫描间的变化系数分别为40.7%、35.2%和53.7%,Bayes方法计算获得的参数值D和f的变化系数低于NLLS方法,前者一致性更好;NLLS方法计算获得的参数值D\*的变化系数低于Bayes方法,前者一致性更好。**结论:**基于双指数模型,可以采用两种方法进行计算,Bayes方法计算获取D和f值,NLLS方法计算获取D\*值,以提升肾脏皮质各个定量参数的稳定性和可靠性。

**【关键词】**肾脏皮质;弥散加权成像;不相干运动;双指数模型

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## Repeatability study on quantization parameters of intravoxel incoherent motion obtained by different estimation methods

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**Abstract: Objective** To study the repeatability of intravoxel incoherent motion (IVIM) parameters of diffusion weighted imaging (DWI) in normal renal cortex obtained by two different estimation methods. **Methods** Eighteen volunteers were enrolled and underwent free-breathing abdominal-renal multi-b-value DWI twice using Philips Ingenia 3.0T magnetic resonance imaging equipment. Based on the double exponential model, the quantization parameter maps (D, D\*, f) of IVIM were calculated from multi-b-value DWI data using non-linear least squares (NLLS) method and Bayesian estimation (Bayes) method. Three equally sized regions of interest were selected from bilateral renal cortex, and the mean of each parameter was calculated. The repeatability of each parameter estimated by the two methods was analyzed using Bland-Altman method. **Results** The coefficients of variation of parameters D, f, and D\* calculated by Bayes method between two scans were 37.4%, 30.0%, and 64.0%, respectively; while those calculated by NLLS method between two scans were 40.7%, 35.2%, and 53.7%, respectively. The coefficients of variation of parameters D and f calculated by Bayes method were lower than those of NLLS method, indicating that Bayes method had better consistency; and the coefficient of variation of D\* obtained by NLLS method was lower than that of Bayes method, indicating that NLLS method had better consistency. **Conclusion** The stability and reliability of various quantitative parameters in the renal cortex can be improved by two methods based on double exponential model: using Bayes method to obtain parameters D and f, and using NLLS method to obtain parameter D\*.

**Keywords:** renal cortex; diffusion weighted imaging; incoherent motion; double exponential model

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## 前言

磁共振弥散加权成像(Diffusion Weighted Imaging, DWI)因其能在分子水平上观测到水分子的运动而具有十分重要的应用价值<sup>[1-2]</sup>。随着磁共振设

备软硬件技术的快速发展,DWI在临床中的应用越来越广泛,而今已成为临床中最常用的检查技术之一<sup>[3-4]</sup>。DWI在肾脏疾病的检出、定性和疗效评估中的应用越来越多<sup>[5-7]</sup>。然而,传统的DWI数据拟合多采用单指数模型,即DWI信号强度随着梯度因子b值的增高而呈单指数衰减的趋势<sup>[8-9]</sup>,单指数模型能很好地反映组织中水分子的运动程度<sup>[10]</sup>。有研究表明DWI信号衰减同时受到水分子自由扩散和微循环血流灌注两种成分的影响<sup>[11]</sup>。因此,运用体素内不相干运动(Intravoxel Incoherent Motion, IVIM),通过双指数模型拟合来描述DWI信号的扩散情况能反映水分子自由扩散和微循环血流灌注信息<sup>[12-13]</sup>。已有研究探讨IVIM在肾脏中的应用,结果表明IVIM在肾脏疾病的定性和疗效评估中有着重要的价值<sup>[14-16]</sup>。为使研究结果更可靠和有效,需要确保IVIM参数估计的可靠性,即是否具有较高的可重复性。因此,本研究旨在评价不同参数估计方法获得的IVIM量化参数在肾脏皮质中的可重复性,为IVIM参数提供一种有效的量化方法,获取更稳定的参数估计方法,为临床提供有效的辅助诊断信息。

## 1 方法

### 1.1 检查方法

所有实验数据均为身体健康且既往无任何肾脏疾病的志愿者,使用飞利浦Ingenia 3.0T超导核磁共振成像仪进行扫描。采用自由呼吸单次激发平面回波成像序列<sup>[17]</sup>,扫描参数如下:TR 1 600 ms;TE 62 ms;矩阵256×256;分辨率1.46 mm×1.46 mm;层厚5.0 mm;层间隔0 mm;层数30;采用多b值扫描<sup>[18]</sup>,b值分别设置为10、20、40、80、200、400、600、1 000 s/mm<sup>2</sup>,其对应的激励次数分别设置为1、1、1、1、1、2、4,两次扫描定位范围保持一致。

### 1.2 实验方法

分别采用非线性最小二乘参数估计方法(Non-Linear Least Squares, NLLS)<sup>[19-20]</sup>和贝叶斯参数估计方法(Bayesian Estimation, Bayes)<sup>[21-22]</sup>估计IVIM参数,获得这两种方法对应的IVIM参数(真性扩散系数D、假性扩散系数D\*和灌注分数f)的图像<sup>[23]</sup>。对两组数据分别采用NLLS和Bayes方法测得的D、D\*和f数据的均值,分别计算其变化系数,使用Bland-Altman方法分别评价两种估计方法在18个志愿者中测量的IVIM参数(D、D\*和f)的可重复性<sup>[24-26]</sup>。

### 1.3 图像处理及参数值测量

利用MATLAB 2021软件分别用NLLS和Bayes方法计算生成IVIM参数图(D、D\*和f)。选取图像信号均匀且无明显运动伪影的肾门扫描层面为标准

层,在左右侧肾脏的皮质区域中分别勾画3个大小一致的感兴趣区进行分析(图1)。

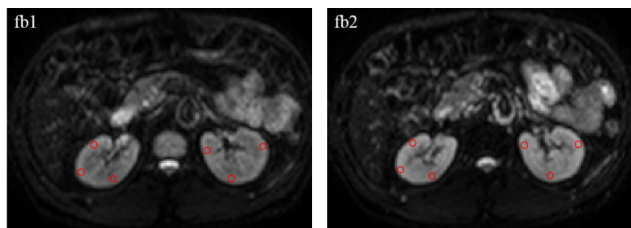


图1 两次采集的同一层面的肾脏图像

Figure 1 Two renal images collected at the same layer

红色圆圈为分别在左右肾脏皮质区域各选取的3个感兴趣区域。fb1为第一次自由呼吸采集图像数据,fb2为第二次自由呼吸采集图像数据

## 2 结果

图2为IVIM模型获得的D值参数图。可以看出,用Bayes方法获得的D值参数图相比用NLLS方法获得的D值参数图更平滑;用NLLS方法获得的参数图D有一些突变点。

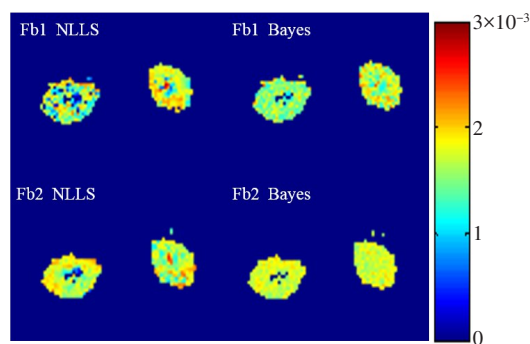


图2 肾脏D值的参数图

Figure 2 D value of the kidney

图3为IVIM模型获得的D\*参数图。可以看出,NLLS方法获得的D\*参数图边界值点较多;用Bayes方法获得的D\*参数图更为平滑,肾脏皮质区域没有出现极限值点。

图4为IVIM模型获得的f值参数图。可以看出,Bayes方法获得的f值参数图更为平滑,第一次自由呼吸用Bayes方法获得的f值参数图仍存在一些边界值点。

图5为两次自由呼吸的Bland-Altman图。Bayes方法在两次自由呼吸状态下获得参数值D、D\*和f的变化系数分别为37.4%、64.0%和30.0%;NLLS方法获得的参数值D、D\*和f的变化系数分别为40.7%、53.7%和35.2%。用Bayes方法获得的D和f值在两

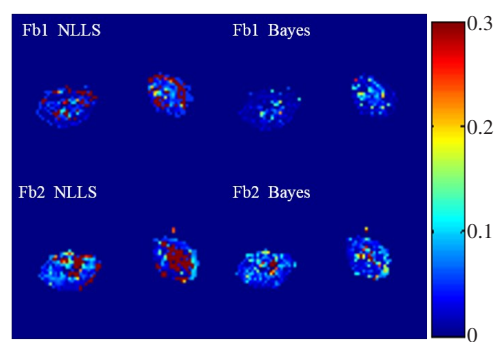


图3 肾脏D\*值的参数图  
Figure 3 D\* value of the kidney

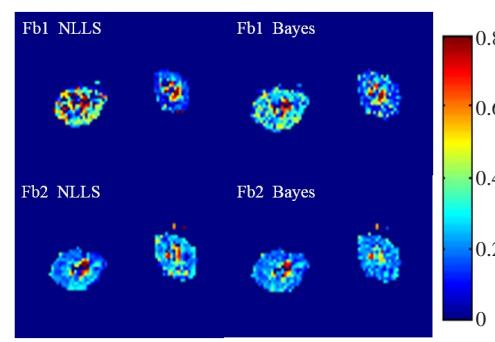


图4 肾脏f值的参数图  
Figure 4 f value of the kidney

次自由呼吸之间其标准偏差更小、一致性更好;用 NLLS方法获得的D\*值在两次自由呼吸之间,其标准差较于Bayes方法更小,一致性更好。

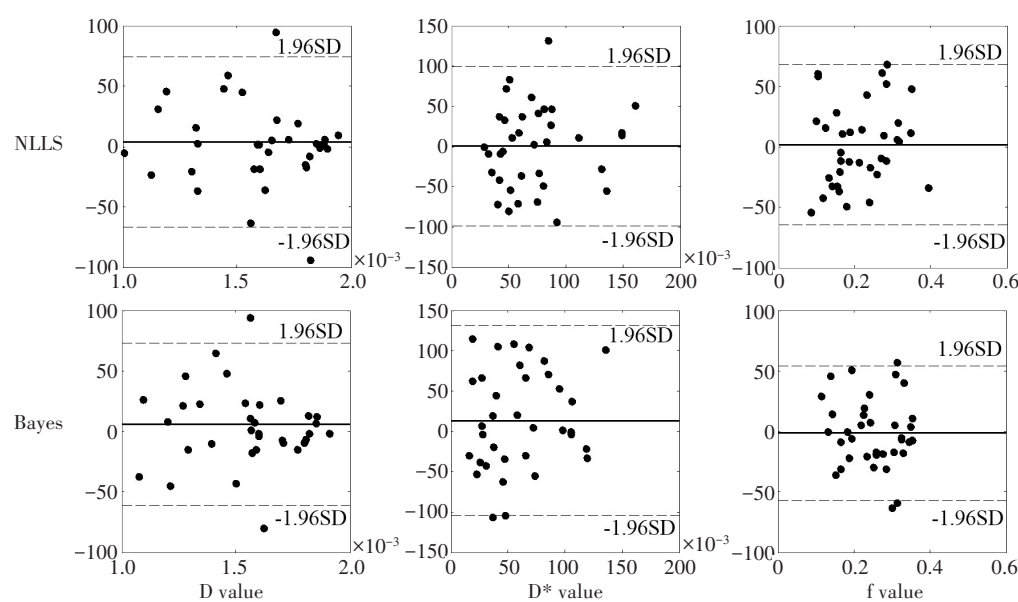


图5 两次自由呼吸采集获得的IVIM参数(D、D\*和f)的Bland–Altman图  
Figure 5 Bland–Altman plots of IVIM parameters (D, D\*, and f) obtained from two free–breathing DWI

3 结论与讨论

用NLLS方法求得的参数在信号噪声服从高斯分布的时候等价于极大似然估计<sup>[27]</sup>。每个体素点都寻找一个均方根误差最小的结果,其准确性和可靠性在信号噪声服从高斯分布的时候能产生无偏的估计结果。Bayes方法是基于参数图服从高斯分布的假设,再用NLLS方法获得参数值进行初始化,迭代求解满足服从正态分布的参数图,与此同时,保持整个图像的均方根误差最小。Bayes的这种假设一定程度上能保持图像的平滑性,减少图像中的极限值点,同时减少某些突变的噪声对参数估计的影响,然而,这种处理也可能改变图像本身的实际的参数值。

Bayes方法能平滑图像,保证图像在视觉效果上的一致性,这样的平滑效果一定程度上能提高两次自由呼吸获得参数值的一致性。Bayes方法是在NLLS方法获得参数值后进行多次迭代获得的结果,其较于NLLS方法更耗时。

现有研究中,IVIM-DWI具有反映组织的水分子扩散状态及血流灌注情况的优势,IVIM参数值在肾脏原发性疾病的良恶性鉴别、恶性肿瘤疗效评估以及肾脏继发性疾病的诊疗中都有重要的意义,不同的疾病也会引起IVIM参数值产生不同的变化趋势。本研究是在自由呼吸下采集数据,无论用NLLS方法或者Bayes方法,其一致性程度都较低,其一致性程



度影响因素可能是由于自由呼吸运动或者腹腔脏器运动产生的位移影响所导致。下一步的研究拟通过呼吸触发的扫描方法来采集数据,以保证不同b值图像之间各个体素对齐,减少呼吸运动对参数估计的影响,并进一步扩大样本量,保证实验的准确性,从而进一步研究IVIM不同参数值变化趋势在肾脏疾病乃至全身多脏器疾病的辅助诊断中的应用价值。

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