INTRODUCTION: Pulsed and pseudo-continuous ASL methods have shown promising perfusion results in native kidneys [1, 2]. ASL-FAIR perfusion calculation depends on Equation 1 below, where \( \lambda \) is partition coefficient, IF = inversion factor, \( \Delta M \) = signal difference between tag and control. Thus the accuracy of the perfusion results depend on the value and consistency of IF, TI, and proton density (M₀). The IF depends on rf-amplifier performance, stability and pulse design, while the TI₁ and M₀ are both patient-specific parameters that can vary regionally and with kidney disease and setting. The model also assumes there is no motion between the tagged and control images or for consecutive tag-control pairs. In practice these assumptions are not always met. This work optimizes an existing pulsed ASL method (FAIR-Fiesta [2]) in order to robustly measure cortical kidney perfusion in patients with diminished renal function, including transplant patients. Motion compensation methods, kidney-specific Ti₁ information, and a measured inversion factor (to address instabilities in the rf-amplifier) are incorporated into perfusion measurement and calculation.

\[
f = \frac{\lambda}{\text{IF} \cdot \text{TI}} \cdot \frac{\Delta M}{M_0} \cdot \exp \left( \frac{\text{TI}}{\text{TI}_1} \right)
\]  

\[1\]

MATERIALS AND METHODS: This HIPAA compliant study was approved by our institutional human subjects review committee and written informed consent was obtained from all subjects. We recruited 7 subjects with native kidneys and 10 subjects with transplanted kidneys with a broad range of renal function, as determined by estimated glomerular filtration rate (eGFR). From this group, two subjects with diminished renal function, one transplant and one native, were chosen to illustrate how these corrections impact cortical kidney perfusion results. Subjects refrained from fluids for four hours prior to the MRI examination.

Scans were performed on a 1.5 T MR scanner (Excite HD, GE Healthcare, Milwaukee, WI, USA) with an eight-element phased array cardiac coil (GE Healthcare, Milwaukee, WI, USA). ASL images were acquired using a 20 ms hyperbolic secant adiabatic inversion pulse in a FAIR-Fiesta technique [2] with the following readout parameters: TR/TE/flip = 4.6/2.3ms/70°, BW = 83.33 kHz, FOV = 34-36 cm, and 128 x 128 matrix. An 8 mm slice was chosen coronal to the kidney, taking care not to include the feeding vessels. Following an inversion time (TI) of 1.2 sec, a centric phase encoded balanced-SSFSE image was acquired. Control and tagged images were alternated until 64 (32 pairs) were acquired. ASL perfusion exams were analyzed using custom scripts written in MATLAB (MATLAB version 8.0, The MathWorks Inc., Cambridge, MA, USA).

Prospective motion compensation: The technique minimized motion corruption by respiratory triggering the inversion pulse after exhalation. Respiratory coaching was also necessary because of a 1.2 sec inversion time delay prior to readout during which the kidney needed to remain stationary. Thus, the subject was instructed to wait for the completion of the image readout noise before inhaling again.

Prospective Ti₁, M₀, and IF Measurement: Additional calibration data was acquired for each subject. M₀ images were acquired at expiration by using the Faia readout with no inversion pulse. Kidney specific Ti₁ information was acquired at expiration for the same FAIR slice using an inversion recovery SSFSE sequence with the following parameters: TR/TE/flop = 4000/25msec, FOV=34-36 cm and 128 x 128 matrices. Six to eight images were acquired for Ti₁-fitting, each with a different inversion time (50ms – 3500ms). The IF for the FAIR adiabatic pulse was determined in a phantom by fitting inversion recovery data to the equation \( M_i = M_0[1-\text{IFexp}(\frac{\Delta M}{M_0})] \) using Levenberg-Marquardt optimization (IF, Ti₁, and M₀ were left as free parameters).

Retrospective motion compensation: When necessary, normalized mutual information (NMI) was used to retrospectively register the Faia images. Automatic and/or manual registration was used to align the SSFSE images when motion was apparent. For automatic alignment, the contrast from images acquired before the null point was inverted to allow gradient registration by minimizing the sum of the square difference. Finally, the kidney in the aligned SSFSE images was registered to the kidney in the aligned Faia images using NMI (gradient or mean based) and/or manual alignment.

Retrospective Ti₁, M₀, and IF correction: A kidney-specific Ti₁ map (smoothed with a 3x3 median filter) was generated by fitting the SSFSE data to the inversion recovery equation in the same manner described above. The kidney was manually segmented from the image and each cortical pixel’s \( \Delta M \), Ti₁, and M₀ value was used to generate a perfusion map. In some cases, the proton density and/or the SSFSE images couldn’t be registered to the FAIR images because of a slice location difference. In these cases, a single average M₀ value and/or a single average cortical Ti₁ value was used. Cortex was brighter than the medulla in the FAIR images and could be differentiated using threshold techniques. ASL perfusion measurements over the cortex were averaged for each kidney.

RESULTS AND DISCUSSION: Perfusion map differences are shown for a transplanted kidney with reduced function (Table 1 and Fig. 1). Perfusion was estimated as 27% lower after correction. Similar corrections for IF, and Ti₁ after spatial registration are shown for a native kidney pair (Table 1 and Fig. 2) also with reduced function. There is much improved delineation of cortical perfusion after correction resulting in a >30% increase in perfusion for both kidneys. A constant Ti₁ = 966ms [3] was used in the uncorrected calculations. Due to motion in the native kidneys, a single M₀ value was used.

Table 1: Kidney | Mean Cortical Perfusion (ml/min/100g) | % Change |
<table>
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<tbody>
<tr>
<td>Uncorrected</td>
<td>Corrected</td>
<td></td>
</tr>
<tr>
<td>Transplant</td>
<td>150</td>
<td>109</td>
</tr>
<tr>
<td>Native RT</td>
<td>273</td>
<td>381</td>
</tr>
<tr>
<td>Native LT</td>
<td>320</td>
<td>423</td>
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</tbody>
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cGFR was 23ml/min/1.73m² for the transplant subject and 23ml/min/1.73m² for the native subject.

CONCLUSIONS: Prospective respiratory gating and self-gated methods are sufficient to allow correction for patient-specific Ti₁, IF and M₀ calculation of perfusion in some cases. However, many cases required retrospective image registration. The impact of patient-specific measures on cortical perfusion calculations can be significant, especially for transplant kidneys where the Ti₁ values appear to be significantly higher and more variable. Moreover, quantitative measures and corrections become increasingly important in longitudinal studies of native and transplant kidney viability.