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Summary

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Purpose: The aim of this study was to explore the information a 4-pool Bloch-McConnell model provides about the NOE contribution in ischaemic stroke, contrasting that with an intentionally approximate 3-pool model.

Methods: MRI data from 12 patients presenting with ischaemic stroke were retrospectively analysed, as well as from 6 animals induced with an ischaemic lesion.

Results: The 4-pool measure of NOEs exhibited a different association with tissue outcome compared to 3-pool approximation in the ischaemic core and in tissue that underwent delayed infarction.

Conclusion: Associations of NOEs with tissue pathology were found using the 4-pool metric that were not observed using the 3-pool approximation.

KEYWORDS:
keyword1, keyword2, keyword3, keyword4

WORD COUNT: XXX

1 | INTRODUCTION

2 | THEORY

The extended phase graph (EPG)[?] decompose the magnetization into a series of fourier coefficients in the transverse plane ($F(k_n)$) and longitudinal axis ($Z(k_n)$) in equation **??**

$$\begin{cases} F(k_n) &= \frac{1}{2\pi}\int_{-\pi}^{\pi} M_{xy}(\theta)e^{-jn\theta}d\theta, \quad n\in\mathbb{Z} \\ Z(k_n) &= \frac{1}{2\pi}\int_{-\pi}^{\pi} M_{z}(\theta)e^{-jn\theta}d\theta, \quad n\in\mathbb{N} \end{cases} \tag{1}$$

$$k_n = n\phi_{\text{inc}} = n\gamma\int_0^{t_{\text{inc}}} G_{\text{RO}}(\tau)d\tau = n\gamma G_{\text{RO}}t_{\text{inc}} \tag{2}$$

The RF pulse induced rotation of the magnetization could be regarded as independent rotation of each isochromat. The rotation of the n-th isochromat is given by

*This is an example for title footnote.

$$\begin{bmatrix} F^+(k_n) \\ F^+(k_{-n}) \\ Z^+(k_n) \end{bmatrix} = \mathbf{R}(\theta,\phi) \begin{bmatrix} F^-(k_n) \\ F^-(k_{-n}) \\ Z^-(k_n) \end{bmatrix} \tag{3}$$

where the rotation matrix $\mathbf{R}(\theta,\phi)$ is given by

$$\mathbf{R}(\theta,\phi) = \begin{bmatrix} \cos^2\frac{\alpha}{2} & e^{2i\phi}\sin^2\frac{\alpha}{2} & -ie^{i\phi}\sin\alpha \\ e^{-2i\phi}\sin^2\frac{\alpha}{2} & \cos^2\frac{\alpha}{2} & ie^{-i\phi}\sin\alpha \\ -\frac{i}{2}e^{-i\phi}\sin\alpha & \frac{i}{2}e^{i\phi}\sin\alpha & \cos\alpha \end{bmatrix} \tag{4}$$

The evolution of states between the RF pulses is given by

$$\begin{aligned} F^-(k_{n+1}) &= E_2F^+(k_n) \\ Z^-(k_{n+1}) &= E_1Z^+(k_n), \quad n \neq 0 \\ Z^-(k_0) &= E_1Z^+(k_0) + M_0(1-E_1) \end{aligned} \tag{5}$$

Under the steady-state condition, the analytic solution for the n-th coefficient of the transverse magnetization after the RF pulse $F^+(k_n)$ has been fully investigated by Leupold[?] , which is given by equation **??**.

$$\begin{aligned} F^+(k_n) = &\frac{M_0(1-E_1)\sin\alpha}{(A-BE_2^2)\sqrt{1-a^2}} \\ &\cdot \left[\left(\frac{\sqrt{1-a^2}-1}{a} \right)^{|n|} - E_2 \left(\frac{\sqrt{1-a^2}-1}{a} \right)^{|n+1|} \right] \end{aligned} \tag{6}$$

where the coefficients A, B and a are given by

$$\begin{aligned} A &= 1 - E_1\cos(\alpha) \\ B &= E_1 - \cos(\alpha) \\ a &= \frac{E_2(B-A)}{A-BE_2^2} \end{aligned} \tag{7}$$

The simplified expression for $F^+(k_{n\geq 0})$ and $F^+(k_{n<0})$ is derived as

$$\begin{aligned} F^+(k_{n\geq 0}) &= c(1-E_2b)b^n \\ F^+(k_{n<0}) &= c(1-E_2b^{-1})b^{-n} \end{aligned} \tag{8}$$

where the coefficients b and c are given by

$$\begin{aligned} b &= \frac{\sqrt{1-a^2}-1}{a} \\ c &= \frac{M_0(1-E_1)\sin\alpha}{(A-BE_2^2)\sqrt{1-a^2}} \end{aligned} \tag{9}$$

the echo signal $S(\mathrm{TE}_n)$ to be measured is given by

$$\begin{aligned} S_n(\mathrm{TE}_n) = &F_n^+ \cdot \underbrace{e^{-\mathrm{TE}_n/T_2}}_{T_2 \text{ relaxation}} \cdot \underbrace{e^{-|\mathrm{TE}_n+n\mathrm{TR}|/T_2'}}_{T_2' \text{ relaxation}} \\ &\cdot \underbrace{e^{j\Delta\omega_0(\mathrm{TE}_n+n\mathrm{TR})}}_{\text{off-resonance phase}} \cdot \underbrace{e^{j\{[u(n)-1]\pi-\Delta\psi n\}}}_{\text{RF phase-cycle}} \end{aligned} \tag{10}$$

The T_2 and T_2' relaxation terms scale the transverse magnetization after the RF pulse F^+. The off-resonance phase term introduce the phase shift of the n-th echo due to the B0 field inhomogeneity, where $\Delta\omega_0 = 2\pi\gamma\Delta B_0$.

The phase-cycle term which was not included in Leupold's paper represent the phase increment of the n-th echo due to the phase-cycling of the RF pulse, where $\Delta\psi$ is the phase increment between the RF pulses and $u(n)$ corresponds to the unit step function.

$$u(n) = \begin{cases} 1, & n \geq 0 \\ 0, & n < 0 \end{cases} \tag{11}$$

The B_0 field map could be estimated by the phase difference between the echoes.

In our sequence, we acquire adjacent echoes with fixed echo spacing $\Delta\mathrm{TE}$. The signal intensity of the n-th echo is expressed as $\mathrm{TE}_n = \mathrm{TE}_0 + n\Delta\mathrm{TE}$

The logarithm of the signal intensityis linearly related to n. For simplicity, we replace the linear coefficient term with μ^+ and μ^-, and the residual term with λ^+ and λ^-.

$$\log\left[|S(\mathrm{TE}_n)|\right] = \log(|F^+(k_n)|) - \frac{\mathrm{TE}_n}{T_2} - \frac{|\mathrm{TE}_n + n\mathrm{TR}|}{T_2'} \tag{12}$$

$$\begin{aligned} \log\left[|S(\mathrm{TE}_{n\geq 0})|\right] &= \log\left[c(1-E_2b)\right] + n\log(b) - \frac{\mathrm{TE}_n}{T_2} - \frac{\mathrm{TE}_n + n\mathrm{T}}{T_2'} \\ &= \left[\log(b) - \frac{\Delta\mathrm{TE}}{T_2} - \frac{\Delta\mathrm{TE}+\mathrm{TR}}{T_2'}\right] n + \Big\{ \log\left[c(1 - \right. \\ &= \lambda^+ n + \mu^+ \end{aligned} \tag{13}$$

$$\begin{aligned} \log\left[|S(\mathrm{TE}_{n<0})|\right] &= \log\left[-c(1-E_2b^{-1})\right] - n\log(b) - \frac{\mathrm{TE}_n}{T_2} + \frac{\mathrm{TE}_n +}{T} \\ &= \left[-\log(b) - \frac{\Delta\mathrm{TE}}{T_2} + \frac{\Delta\mathrm{TE}+\mathrm{TR}}{T_2'}\right] n + \Big\{ \log\left[-c(\right. \\ &= \lambda^- n + \mu^- \end{aligned} \tag{14}$$

The total signal intensity of the echoes is given by

$$\begin{aligned} \sum_{n=-\infty}^{\infty} |S(\mathrm{TE}_n)| &= \sum_{n=0}^{\infty} e^{\lambda^+ n + \mu^+} + \sum_{n=-\infty}^{-1} e^{\lambda^- n + \mu^-} \\ &= \frac{e^{\mu^+}}{1-e^{\lambda^+}} + \frac{e^{\mu^-}}{e^{\lambda^-}-1} \\ &= \frac{c(1-E_2b)e^{-\mathrm{TE}_0/T_2 - \mathrm{TE}_0/T_2'}}{1-be^{-\Delta\mathrm{TE}/T_2+(\Delta\mathrm{TE}+\mathrm{TR})/T_2'}} + \frac{-c(1-E_2b^{-1})e}{b^{-1}e^{-\Delta\mathrm{TE}/T_2+(\Delta}} \end{aligned}$$

The magnitude sum of all the echoes is different from the signal intensity of the bSSFP sequence. The bSSFP image contrast as well as the banding artifacts could be readily generated by the complex sum of the echoes. The dark band is due to the phase cancellation from

$$
\begin{aligned}
S_{\mathrm{bSSFP(banding)}} &= \sum_{n=-\infty}^{\infty} S(\mathrm{TE}_n) \\
&= \sum_{n=0}^{\infty} e^{\lambda^+ n+\mu^+ +j[\Delta\omega_0(\mathrm{TE}_n+n\mathrm{TR})-\Delta\psi n]} + \sum_{n=-\infty}^{-1} e^{\lambda^- n+\mu^- +j[\Delta\omega_0(\mathrm{TE}_n+n\mathrm{TR})+\pi-\Delta\psi n]} \\
&= \frac{e^{\mu^+ + j\Delta\omega_0 \mathrm{TE}_0}}{1-e^{\lambda^+ + j[\Delta\omega_0(\Delta\mathrm{TE}+\mathrm{TR})-\Delta\psi]}} + \frac{e^{\mu^- + j\Delta\omega_0 \mathrm{TE}_0}}{1-e^{\lambda^- + j[\Delta\omega_0(\Delta\mathrm{TE}+\mathrm{TR})-\Delta\psi]}}
\end{aligned}
$$

To generate the bSSFP image contrast without banding from the MESS echoes, it's straightforward to neglect the off-resonance phase term. The phase-cycle term should be preserved to maintain the image contrast.

$$
\begin{aligned}
S_{\mathrm{bSSFP(no\ banding)}} &= \sum_{n=-\infty}^{\infty} |S(\mathrm{TE}_n)| e^{\{[u(n)-1]\pi-\Delta\psi n\}} \quad = \sum_{n=0}^{\infty} e^{\lambda^+ n+\mu^+ +j[\Delta\omega_0(\mathrm{TE}_n+n\mathrm{TR})-\Delta\psi n]} + \sum_{n=-\infty}^{-1} e^{\lambda^- n+\mu^- +j[\Delta\omega_0(\mathrm{TE}_n+n\mathrm{TR})+} \\
&= \frac{e^{\mu^+}}{1-e^{\lambda^+ - j\Delta\psi}} + \frac{e^{\mu^-}}{1-e^{\lambda^- - j\Delta\psi}}
\end{aligned}
$$

3 | METHODS

3.1 | Pulse Sequence Generation

3.2 | Simulation Experiments

3.3 | Phantom and In Vivo Experiments

4 | RESULTS

5 | DISCUSSION

6 | CONCLUSION

ACKNOWLEDGMENTS

Author contributions

This is an author contribution text. This is an author contribution text. This is an author contribution text. This is an author contribution text. This is an author contribution text. This is an author contribution text.

Financial disclosure

None reported.

Conflict of interest

The authors declare no potential conflict of interests.

SUPPORTING INFORMATION

The following supporting information is available as part of the online article:

Figure S1. 500 hPa geopotential anomalies for GC2C calculated against the ERA Interim reanalysis. The period is 1989–2008.

Figure S2. The SST anomalies for GC2C calculated against the observations (OIsst).

How to cite this article: Williams K., B. Hoskins, R. Lee, G. Masato, and T. Woollings (2016), A regime analysis of Atlantic winter jet variability applied to evaluate HadGEM3-GC2, *Magn. Reson. Med., 2017;00:1–6.*

APPENDIX

A SECTION TITLE OF FIRST APPENDIX

Use `\begin{verbatim}...\end{verbatim}` for program codes without math. Use `\begin{alltt}...\end{alltt}` for program codes with math. Based on the text provided inside the optional argument of `\begin{code}[Psecode|Listing|Box|Code|Specification|Procedure|Sourcecode|Program]...\end{code}` tag corresponding boxed like floats are generated. Also note that `\begin{code}[Code|Listing]... \end{code}` tag with either Code or Listing text as optional argument text are set with computer modern typewriter font. All other code environments are set with normal text font. Refer below example:

Listing 1 Descriptive Caption Text

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{ do nothing }
end;
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WritE('Pascal keywords.');
```

A.1 Subsection title of first appendix

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A.1.1 Subsection title of first appendix

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B SECTION TITLE OF SECOND APPENDIX

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B.1 Subsection title of second appendix

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$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} - m\bar{\psi}\psi \tag{B1}$$

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TABLE B1 This is an example of Appendix table showing food requirements of army, navy and airforce.

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