Multiscale Electromagnetic Modeling of Contractions in the Pregnant Uterus

V. Tidwell[1], P. S. La Rosa[2], M. Zhang[1], H. Eswaran[3], A. Nehorai[1]

1. Department of Electrical & Systems Engineering, Washington University in St Louis, St Louis, MO, USA
2. Monsanto Company, Technology Pipeline Solutions, St Louis, MO, USA
3. OB/GYN Department, University of Arkansas for Medical Sciences, Little Rock, AR, USA

This work was supported by the NIH under Grant 1R01EB016567-01A1.

Introduction: Uterine contractions during pregnancy are currently poorly understood – experts disagree on the mechanisms by which contractions propagate through the organ [1] and the structural layout of the uterine muscle fibers [2]. Building on our previous work [3], we have developed a multi-scale model of the uterus, at the cellular, tissue, and organ levels. By comparing simulated abdomen-level magnetic field readings from our model to clinical measurements, we hope to create a framework by which propagation mechanisms and fiber structures can be compared and validated.

Computational Methods: Using COMSOL, we construct an anatomically realistic geometry with four domains (Figure 1a):

- The intra-uterine contents (e.g., fetus and amniotic fluid),
- The uterine muscle,
- The abdomen, and
- The external environment.

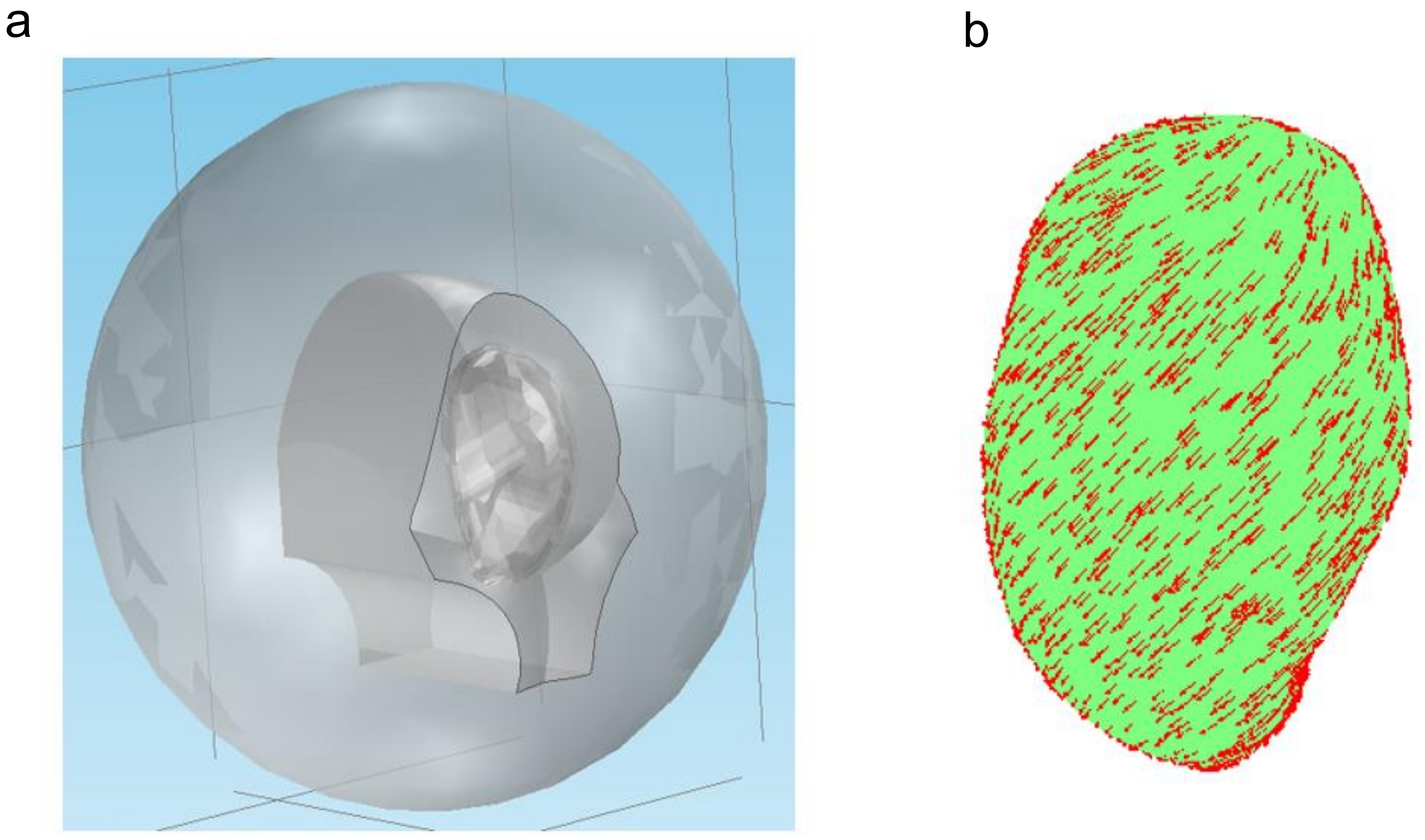

Figure 1. (a) Four domain geometry. (b) Conductivity Tensor within uterine muscle, for a fixed angle.

The transmembrane potential in the uterus is computed using an ionic current model in PDE physics and a time-dependent solver over the uterus domain. These results are then fed first into stationary EC physics to solve for the currents within the abdomen and uterus at a set of time points, and then subsequently into stationary MF physics to solve for the normal component of the magnetic field at the outer surface of the abdomen.

To model the layout of the uterine muscle fibers, we define the conductivity at each point in the uterus domain to lie parallel to the uterus surface at some angle (Figure 1b).

Results: Under the assumption of a uniform conductivity tensor angle, i.e., well-ordered structure to the uterine muscle fibers, and a simple two-variable FitzHugh-Nagumo ionic current model [3] for the PDE physics, a plateau-type transmembrane potential propagates smoothly across the uterine surface (Figure 2). The currents due to this propagation along the uterus surface in turn induce a magnetic field at the abdomen surface (Figure 3).

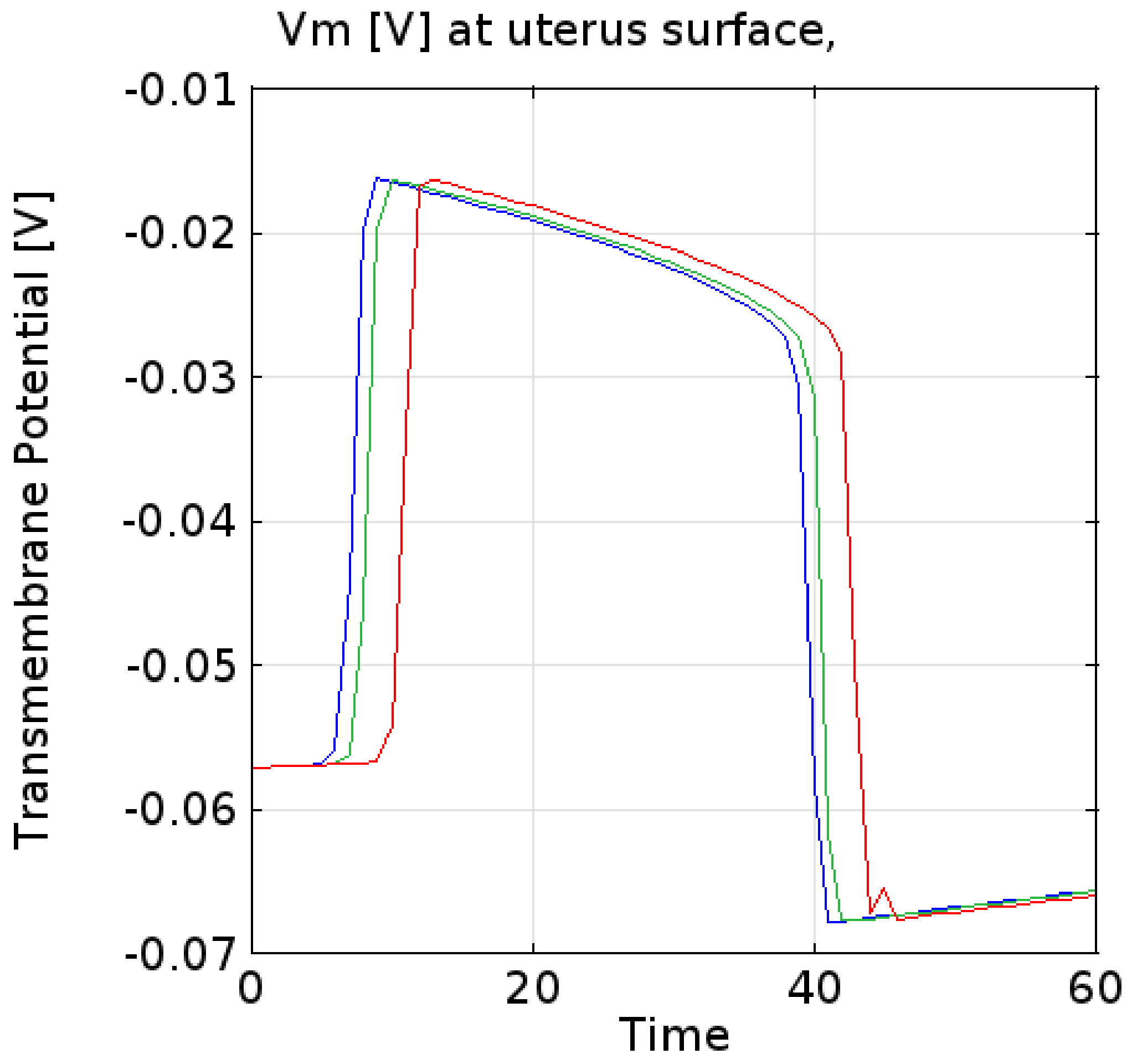

Figure 2. Traces of the transmembrane potential on the front of the uterus surface at three points, 12.4 [cm], 10.75 [cm], and 7.38 [cm] above the midline of the organ.

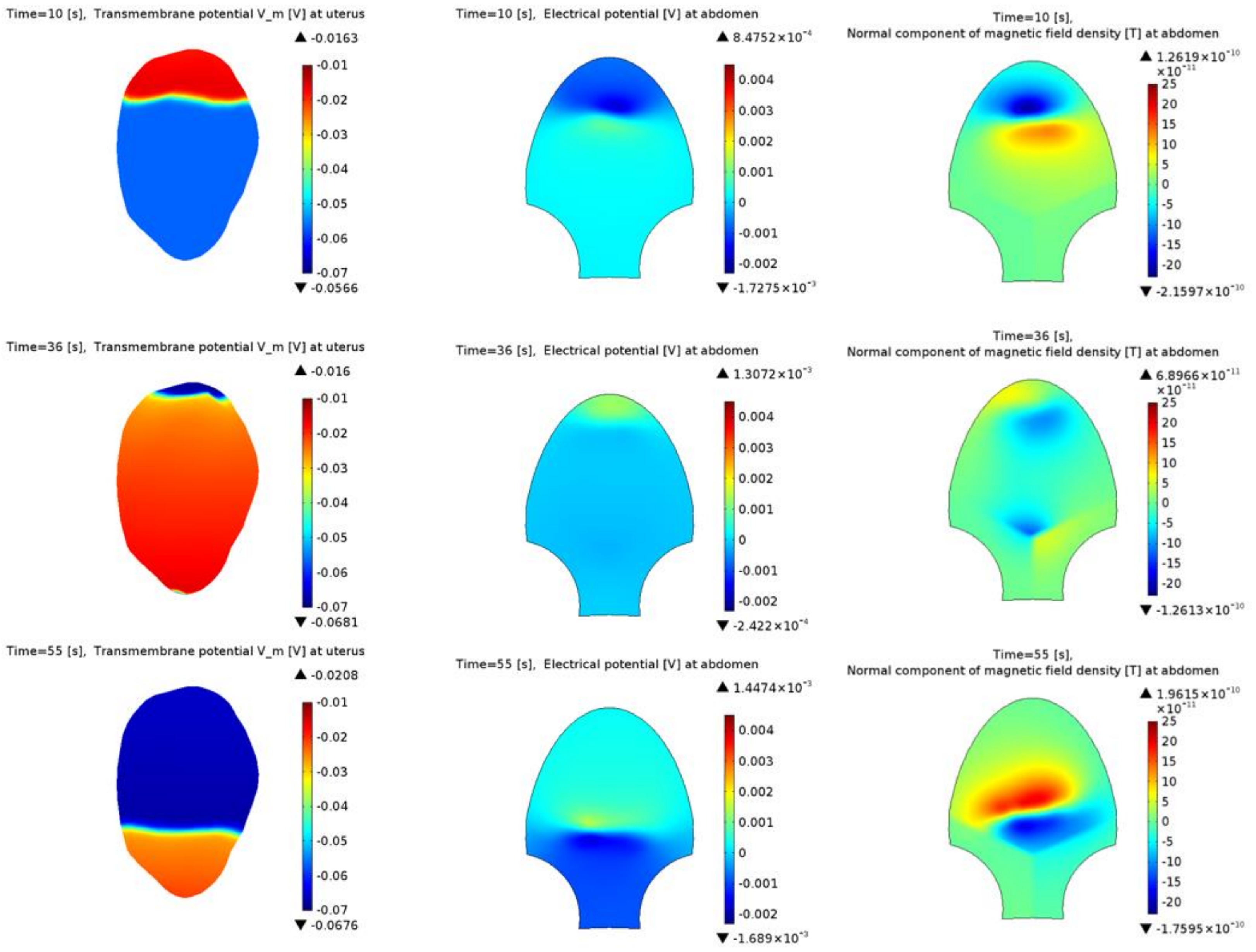

Figure 3. COMSOL solutions at three time points (t = 10 [s], 36 [s], and 55 [s]), following a stimulus current applied at the fundus of the uterus, assuming a uniform angle for the conductivity tensor.

Conclusions: The multi-scale model we have constructed using COMSOL will be invaluable for comparison and validation of differing models for the cellular and organ level properties of the pregnant uterus. By varying these properties within our COMSOL model, we can determine how best to replicate real-world measurement. This in turn will facilitate interpretation of the real-world measurements, allowing the state of the transmembrane potential in the uterus to be estimated from the state of the magnetic field at the abdomen surface.

References:

1. Roger Young, Myocytes, Myometrium, and Uterine Contractions, Ann NY Acad Sci, 1101, 72-84 (2007).
2. Koji Fujimoto et al., Diffusion Tensor Imaging (DTI) of the Normal Human Uterus In Vivo at 3 Tesla: Comparison of DTI Parameters in the Different Uterine Layers, Journal of Magnetic Resonance Imaging, 38, 1494-1500 (2013).
3. Patricio LaRosa et al., Multiscale forward electromagnetic model of uterine contractions during pregnancy, BMC Medical Physics, 12, (2012).