

# A Flexible Flow Model for Gradient Coil Design for the Purpose of Clinical MRI

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**Introduction:** Gradient coil design has been the focus of much research in recent years using many different approaches [1-4] with the aim to produce gradients that have large imaging regions, high field strengths and low acoustic output as a consequence of the action of Lorentz forces. Although many different approaches exist for the design of gradient coils, the process can be tedious and time consuming independent of the design method employed. The proposed approach aims to provide a basis that allows the optimization routine to converge to a wire pattern winding more easily using a formulation that allows for more freedom than, for example, the target field method [5]. The advantage of using the proposed method lies in that the final patterns can be made very freeform, or less freeform, depending on the requirements and the wire flexibility. Because the final patterns can be more freeform than wire patterns obtained using other strategies, for example [1, 6-8], this gives rise to larger imaging regions. Through the optimization special care is taken to try and make sure that the coil inductance, especially for the transverse windings, is low to allow for competitive rise times. The Flow Model for Gradient Coil Design (FMGCD) numerical solution for a full body cylindrical gradient coil set is benchmarked against the Siemens Sonata gradient set to establish the quality of design using the proposed method.

**Method:** The methodology behind FMGCD was conceived by the analogy that fluid may propagate through a porous media with certain density and consequent wave front speeds. Initial work in the field of gradient coil design [3, 4] and literature on segmentation [9] led to the development of the FMGCD algorithm. Fluid flow through a porous media is the basis behind the manner in which wire path patterns are formed. If so desired, then two distinct laminates may be used in the algorithm to obtain the primary and shield windings, but the algorithm also allows for a single porous laminate to be used for both the primary and shield gradient coil windings. The fluid flow wave fronts are essentially the wire path patterns, and the number of these can be changed between the primary and shield windings. Therefore, given certain coil characteristics, mainly current flow direction, inductance and required field strength, the properties of the material in which the fluid propagates can be varied to a level that satisfies the criteria for the particular gradient field. For this proposed method of gradient coil design the fluid is considered to be propagating from a point source in a manner of a wave and is input as multiple pulses. The algorithm utilises the numerical solution of the wave equation for the propagation of the fluid through the porous media. By changing the number of input pulses to the wave equation, multiple wave fronts may be obtained and the number of subsequent wire paths is consequently based on the number of input pulses. Physical separation between wire paths is altered by changing the time delay between the input pulses in the numerical model. For FMGCD to achieve convergence two sets of variables have to be defined, which are the densities of the different cells that the fluid passes through and the time separation between the input pulses that provide the consequent physical wire separations. A simple numerical approach is adopted to solve the wave equation on an inhomogeneous porous 2D domain in the form of a plane or shell. Numerical errors for the solution of the wave equation technique are not considered, because optimization of varying variables is performed, and therefore, any errors are bounded between different iterations. Optimum values for the porous media properties and input time sequence for pulses are obtained through successive iterations of the Simulated Annealing (SA) algorithm [10]. For each iteration of the SA algorithm the wave fronts that constitute the wire paths need to be solved, and from these calculations appropriate field components can be obtained using the Biot-Savart law.

**Results:** Using the FMGCD algorithm a set of full-body cylindrical gradient coils was designed. The main results of the FMGCD gradient coils are listed in Table 1, and are compared to the Siemens Sonata gradient coil set. From Table 1 it can be seen that using FMGCD the dimension of the gradient coils is comparative in radius, but is smaller in length. Although it should be noted that for the Siemens Sonata gradient coil set the dimensions are external, and for the FMGCD results the dimensions are primarily for the coil windings. From these results it can be seen that the imaging region using the FMGCD algorithm is quite large, when compared to the Siemens Sonata set of data. In Table 1 the efficiency is a measure of the gradient strength and is comparable for both cases. It is hard to compare inductances directly, because no exact numbers are provided for these for the Siemens Sonata gradient coils, but it still gives an indication of the rise time of the coils. Switching efficiency for the FMGCD gradients coils is greater, and this is primarily because the size of the imaging region is larger in volume. The efficiency being reasonably consistent between the different gradient coil designs means that this does not significantly impact the switching efficiency, and therefore, the primary advantage lies in the ability of FMGCD to produce large imaging regions.

Description	Siemens Sonata Gradient Coil Set			Flow Model for Gradient Coil Design (FMGCD)		
	x	y	z	x	y	z
Gradient coil						
Dimension (D cm × Z cm)	67 – 88 × 1.235			68.8 × 110	70 × 110	73.2 × 110
Inductance (μH)	< 800			571	553	230
Efficiency (mTm <sup>-1</sup> A <sup>-1</sup> )	0.080			0.090	0.085	0.080
FOV diameter (cm) @ 5%	22 @ 3.5%, 30 @ 7%, 40 @ 15%			40	42	47
FOV diameter (cm) @ 20%				48	50	56
Switching efficiency @ 20%	0.0155 @ 7%, 0.065 @ 15%			0.2876	0.3249	1.2195

**Table 1.** Comparison of key measures of the Siemens Sonata gradient coil set to that obtained using FMGCD.

**Conclusion:** In this work a method of wave propagation through porous media is investigated. The FMGCD method was used to design a cylindrical set of body gradient coils. Comparisons between a set of gradient coils obtained using FMGCD and the Siemens Sonata gradient coil set was performed. It was shown that the FMGCD method can produce large imaging regions, and consequently the switching efficiency of the gradient coils obtained using FMGCD is better than that of the Siemens Sonata gradient coils. The rise time of the gradient coils obtained from FMGCD are comparative to that of the Siemens Sonata gradient coils. This conclusion is drawn by taking into account the maximum inductance of the Siemens Sonata gradient coils and stating that all inductances in the FMGCD gradient coils are less than that of the upper bound of the Siemens Sonata gradient coil set.

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