Abstract. As an effective and noninvasive therapeutic modality for tumor treatment, high-intensity focused ultrasound (HIFU) has attracted attention from both physicians and patients. New generations of HIFU systems with the ability to electrically steer the HIFU focus using phased array transducers have been under development. The presence of side and grating lobes may cause undesired thermal accumulation at the interface of the coupling medium (i.e. water) and skin, or in the intervening tissue. Although sparse randomly distributed piston elements could reduce the amplitude of grating lobes, there are theoretically no grating lobes with the use of concave elements in the new phased array HIFU. A new HIFU transmission strategy is proposed in this study, firing a number of but not all elements for a certain period and then changing to another group for the next firing sequence. The advantages are: 1) the asymmetric position of active elements may reduce the side lobes, and 2) each element has some resting time during the entire HIFU ablation (up to several hours for some clinical applications) so that the decreasing efficiency of the transducer due to thermal accumulation is minimized. Genetic algorithm was used for selecting randomly distributed elements in a HIFU array. Amplitudes of the first side lobes at the focal plane were used as the fitness value in the optimization. Overall, it is suggested that the proposed new strategy could reduce the side lobe and the consequent side-effects, and the genetic algorithm is effective in selecting those randomly distributed elements in a HIFU array.

Keywords: phased array, genetic algorithm, pressure distribution, side lobe

PACS: 43.30.Yj, 43.80.Vj

1. Introduction

High intensity focused ultrasound (HIFU), a noninvasive ablative therapy, is currently the subject of considerable research and development (ter Haar and Coussios 2007). Treatable targets include prostate, pancreatic, liver, breast cancer and uterine fibroids (Wu et al. 2001 and Meaney et al. 2000). Such technology requires precise control of the size and location of the beam focus. Most currently available HIFU systems are based on the use of a single focused transducer or a focusing acoustic lens in front of a piston transducer, and have the advantage of easy manufacture and operation. The acoustic beams produced are, therefore, fixed in shape and position, and modification of the focal size can be accomplished only by changing the physical properties of the transducer (i.e., spherical shell aperture or radius of curvature, or geometries or materials of lens), but not during the course of a procedure. In addition, their significant shortcoming is the need to scan the small focus through the whole target volume by mechanically translating or rotating the transducer, which may lead to impractically long duration of clinical treatments.

The use of phased arrays, which has long been employed in sonar and diagnostic imaging, offers not only electrical steering of a focal ultrasound beam to precise positions and controlling its range, location and size without mechanical motion, but also a means of modifying the characteristics of the ultrasonic surgical beam, such as synthesizing fields with multiple simultaneous foci. Pilot investigations were of the phased piston element array on a spherical shell (Ebbini and Cain 1991 and Goss et al 1996). The
disadvantages of phased arrays include system complexity, relatively high cost, and the presence of grating lobes, particularly with large extracorporeal 2D arrays. Sparse random arrays have long been used in the design of communication antenna systems, and very recently this technology has been applied in ultrasound imaging systems. It was shown theoretically that the use of elements randomly distributed on a segment of a spherical surface may improve phased array performance (Goss et al. 1996). To guarantee sufficient acoustic energy accumulation at the focal point the aperture size of the transducer needs to be large, which may hinder its application in some clinical cases with limited acoustic window. Hand et al. have proposed the distribution of all elements randomly in the spherical surface to reduce the grating lobes. The feasibility of the focal steering and thermal ablation using a randomized phased array has already been proven in in vitro and ex vivo experiments although with more complexity of system control because of the asymmetrical position of all elements (Hand et al. 2009).

For the development of a HIFU transducer, concave rather than piston elements have been used to build the phased arrays. Since all concave elements share the same spherical surface, the existence of grating lobes due to the symmetrical position of piston elements is no longer a problem. In this study, the concept of the sparse randomized phased array has been applied to reduce the amplitude of side lobes in the focal region to enhance the acoustic energy concentration for HIFU therapy. Genetic algorithm was first used to optimize the element selection. It is shown that the amplitude of side lobes could be reduced by 4 dB after 100 generations in the genetic algorithm. In addition, it is suggested that temporally and spatially randomized phased arrays could also increase the safety of HIFU during a long high-intensity pulse delivery.

2. Methods

A virtual high-intensity focused ultrasound phased array transducer is shown in Figure 1. It consists of 512 elements in 8 even layers on a spherical surface. All elements in the same layer have the same size, which is similar to those in the neighboring layers. The inner and outer diameters of the HIFU transducer are 40 mm and 85 mm, respectively; and the focal length is 140 mm. All elements are driven at a center frequency of 1 MHz, which ensures sufficient penetration of HIFU energy into the abdomen and is typically chosen for clinical extracorporeal HIFU systems. The central hole is to accommodate the ultrasound imaging probe used for the guidance of HIFU therapy and monitoring of the thermal lesion production.

![FIGURE 1. Schematic illustration of the virtual phased array high-intensity focused ultrasound transducer.](image-url)
The pressure distribution in the focal region can be simulated using a classic Rayleigh integration
method. For simplicity, no nonlinear effects are considered in the ultrasound beam propagation and
focusing.

\[
p(x, y, z) = \iint \frac{j k \rho_0 c_0}{2 \pi h} u_A e^{i(\omega t - k h)} dS
\]

where \( j = \sqrt{-1} \), \( k = \omega / c_0 \) is the wave number, \( \omega \) is the angular frequency, \( c_0 \) is the small-amplitude
sound speed in water, \( \rho_0 \) is the equilibrium density of water, \( x_0, y_0, \) and \( z_0 \) are the coordinates of the active
elements of the HIFU phased array transducer \( (S) \), \( x, y, \) and \( z \) are the coordinates in the focal region of
HIFU transducer, \( h \) is the distance between the point source on the transducer surface and the focal region,
\( u_A \) is the velocity of the transducer surface. The simulated acoustic pressure will then be normalized by
the peak pressure at the focal point because in linear acoustics the peak pressure at the focus is
proportional to the area of the active elements taking into account the same vibration on the surface of the
transducer and our major interest is the characteristics of pressure distribution, not its absolute value.

Genetic algorithm (GA) is a search algorithm based on the simulation of chromosome evolution
occurring in the nature. Unlike a traditional point-by-point searching approach throughout the whole
variable space, such as least square method, GA constitutes a parallel search of variables for global
optimal solutions. There are three fundamental operators in the GA: selection, cross-over, and mutation as
shown in Fig. 2. 20% of parent chromosomes with the best fitness values will be selected to breed a new
generation. Crossover is a genetic operator used to vary the programming of a chromosome or
chromosomes from one generation to the next. Two-point crossover as used in our operation calls for two
points to be selected on the parent organism strings. Everything between the two points is swapped
between the parent organisms, rendering two child organisms. Mutation, changing one or several arbitrary
bits in a genetic sequence from its original state, is a genetic operator used to maintain genetic diversity
from one generation of a population of algorithm chromosomes to the next. Chromosome, the potential
solutions in the GA evolution, and fitness function, the evaluation of the solution, are two essentials in the
operation. Here the chromosome is a 512-bit string with each bit presenting an element in the phased
array transducer (1 for active and 0 for idle). Fitness function is defined as the sum of the normalized peak
pressures of the 1st side lobes at the lateral directions (X and Y). There are in total 20 chromosomes and
initially all of their bits are 1. The fitness of each chromosome (solution) will be calculated using
Rayleigh integration method as described in Eq. (1), then operation of selection, cross-over, and mutation
will be carried out among these 20 chromosomes for the next new generation. GA terminates after 100
generations to show the optimization results (see Fig. 3). Optimization is run in the Matlab environment using its Direct Search and Genetic Algorithm toolbox (Mathworks, Natick, MA, USA).

3. Results

When all elements are activated, the first side lobe appears at 1.8 mm away from the focal point in the lateral direction with a normalized pressure of 0.3092 (see Fig. 5b). The fitness value of the chromosomes group decreases significantly after running the genetic algorithm. After 30 generations the slope becomes much smaller. The difference between the best fitness and mean fitness is within 20% (see Fig. 4). The best selection after 100 generations of genetic evolution is shown in Fig. 5a (red for active elements and green for idle ones). It is interesting to note that the percentage of active elements (317/512) is close to the golden ratio, 0.618, and most of these active elements are distributed along either the X or Y axis,
which is similar to the design of the sparse array in the ultrasound imaging probe. The peaks of the first side lobe in the X and Y directions are 0.1972 and 0.187, or 3.9 dB and 4.4 dB lower than that with all elements activated (uniform source distribution on the spherical shell), respectively. The pressure distribution at the focal plane, either in the X or Y direction, shows a great symmetry (discrepancy of less than 1%) with respect to the transducer axis. However, the locations of nodes move closer to the focal point (3.9 vs. 3.6 mm and 2.6 vs. 2.3 mm for the 3rd and 2nd nodes), and the amplitudes of the 2nd and 3rd side lobes are significantly increased (0.148/0.1767 vs. 0.1226 and 0.119/0.1389 vs. 0.0537 in the format of pressure in X/Y direction vs. that of with all elements activated as seen in Fig. 5b).

![Figure 5](image)

**FIGURE 5.** (a) Top view of the best selection of phased array elements after 100 generations in the genetic algorithm and (b) the simulated pressure distribution in the lateral direction (X and Y) in comparison to that with all elements activated.

4. Discussion

Phased arrays were initially developed in ultrasound imaging and are being used in high-intensity focused ultrasound for thermal ablation. Their significant advantage is electrical steering of the focal point with the ability to modify the characteristics of the focused ultrasound beam despite the increase in system complexity and cost. However, the existence of grating lobes because the symmetrical position of piston elements leads to reduced imaging resolution and introduction of artifacts in diagnosis, or unintended side effects induced beyond the focal volume during the HIFU therapy. Sparse phased arrays and randomly distributed phased arrays have been applied to reduce grating lobes. With the development of the concave high power transducer grating lobes are not present. It was found that randomly selecting elements in the phased array HIFU transducer can change the characteristics of the pressure distribution at the focal plane. Therefore, it is suggested that certain selection of active elements would concentrate the surgical ultrasound beam more accurately in the main lobe. To optimize the elements selection for the reduced first side lobe, genetic algorithm was tried in this study. The result shows that optimal elements selection leads to about 4 dB reduction in the amplitude of the first side lobe at the focal plane.

Genetic algorithm is a method of solving both constrained and unconstrained optimization problems that is based on natural selection, which drives biological evolution, and repeatedly modifies a population of individual solutions. At each step, genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population evolves toward an optimal solution. The current selection in Fig. 5a is the best results after 100 generations; however, this may not be the global optimal result as the fitness value improves slowly after 20 generations as shown in Fig. 4 since the main purpose of this study is the feasibility of the genetic algorithm in optimizing element selection. The key in determining the
performance of the genetic algorithm is the definition of fitness value, which is the sum of amplitudes of the first side lobe in the both X and Y directions in this study. Our simulation illustrates that although the first side lobe is suppressed, the other higher order side lobes increases. If the amplitudes of all side lobes that cover the acoustic energy in the focal region are included in the fitness function (maybe reversely weighted by their order number), the outcome of pressure distribution will be improved. In addition, skin burns are sometimes found after HIFU treatment and one of the explanations is the temperature elevation induced by one of the pre-focal lobes along the HIFU transducer axis. In future investigations the fitness function could include the pressure characteristics in both lateral and axial directions. Since the beam size in the axial direction (~ 10 mm) is larger than that in the lateral direction (1~3 mm), modifying axial pressure distribution may be of great value in increasing HIFU safety. Furthermore, current phased array technology can not only determine the phase or time delay to each element for electrical steering but also adjust the electrical power to it. The potential aperture apodization provides us with the greater ability to modify the characteristics of the HIFU beam despite the increased complexity in operation, which would also be applied in the acoustic tweezers and drug delivery.

Because of the high power delivered during a HIFU treatment and the limited space of each element in the phased array transducer for cooling in comparison to the single element system, the temperature of the piezoelectric material will increase during therapy. As a result, the electrical-to-acoustic energy conversion efficiency and the stability of the HIFU transducer may be worse. Repair or replacement of those small-size elements needs specific work. After 100 generations in the genetic algorithm, the best result is the 10th chromosome as seen in Fig. 4. However, the fitness values of other chromosomes, such 1st, 2nd, and 16th, are also comparable, which means there exists a group of selections with satisfactory performance. Therefore, phased array elements could also work in the temporally random style. At one time slot a certain selection of elements is used and will be changed to another one at the next time slot. Such a change can be repeated within the group of selections found after the optimization process and stored in the HIFU control system. Since all of these selections are not exactly the same, each element could have some “resting” time during the HIFU treatment which is usually several hours depending on the size of tumor target. Consequently, the lifetime of both transducer and driving circuit would be elongated. Altogether, spatially and temporally random selection of phased array elements of HIFU transducer could change the beam characteristics, and the genetic algorithm is helpful in optimizing the element selection and could be used in other acoustic optimization problems. Enhanced efficiency and safety of the HIFU delivery is expected with the further investigation of beam-forming techniques.

References and links