Biplane ultrasound arrays with integrated multiplexing solution for enhanced diagnostic accuracy in endorectal and transvaginal imaging

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Abstract— *Biplane ultrasonic endocavity probes are nowadays commonly used in many applications such as obstetrics, gynecology or urology. The present work will relate to an innovative probe design that comprises three independent array transducers specifically designed for transrectal diagnostic with respect to brachytherapy protocols and prostate cancer. The transducer set is composed of a short curvature traversely mounted array being sandwiched between the two other curved arrays longitudinally mounted. The curvatures of the transverse and longitudinal transducers are set different to provide extended views of the organ. Rapid switching between transverse and longitudinal devices are provided by the implementation of a multiplexing electronics manageable by the imaging system.*

I. INTRODUCTION

Biplane endorectal and endovaginal probes are nowadays commonly used in many applications such as obstetrics, gynecology, urology.... They are generally composed of 2 arrays one linear for imaging of the longitudinal plane and a highly curved one to image the transverse plane. These two planes allow a perpendicular visualization of region of interest. This is very useful, for example in biopsy procedure in transrectal guidance where radiologist can guide and perform accurately the puncture by placing in the transverse plane the body that needs biopsy and in the longitudinal plane the needle puncture. But biplane probes are very challenging for ultrasound transducer and system engineers, because of the large number of active elements to be managed in these probes. In this work we present an innovative design [1] of probe composed of 3 arrays specifically developed for transrectal imaging, brachytherapy protocol and prostate cancer monitoring.

The first array is a highly curved, with a 6.5MHz center frequency and 96 elements. It is positioned in the transverse plane i.e. orthogonally as compared to probe shaft. Two 96 elements 7MHz center frequency low curvature arrays are positioned in the longitudinal plane of the probe on both sides of the highly curved array. To reduce the number of coaxial cables we integrated electronics in the probe handle to multiplex the 3*96 elements to one 96 conductors coaxial cable, enabling fast switching between arrays and real time display of the 2 images: a transverse one and a longitudinal one obtained by overlapping the two images of the low curvature arrays. But introducing electronic circuits between ultrasound arrays and imaging system must not decrease arrays performances and image quality. Then after describing the probe design, multiplexing electronics and system front-end connectivity, we will show results of complete characterizations: electroacoustic and acoustic with and without electronics in order to evaluate impact of multiplexing circuits on performances.

Finally we present brachytherapy protocol with seeds placement guided by ultrasound imaging and clinical evaluation of the probe.

II. PROBE DESIGN

The concept of this probe is to allow full visualization of the entire prostate with the objective to place the transverse scan in the middle, thus eliminating the need to change the longitudinal position of the transducer along the rectum, and does not induce movement of the prostate.

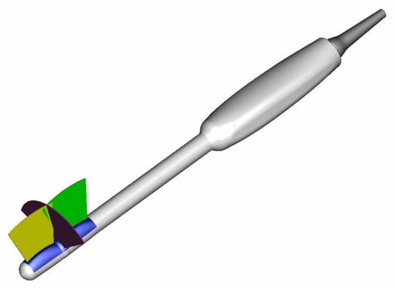

Figure 1 : Illustration showing probe and scan planes provided by the 3 arrays

The probe integrates a highly curved array, with a 6.5MHz center frequency and 96 elements positioned in the transverse plane i.e. orthogonally as compared to probe shaft and two 96 elements 7 MHz center frequency low curvature arrays positioned in the longitudinal plane on both sides of the highly curved array.

	A1&A3	A2
Type	Low curvature linear array	High curvature linear array
Nb of active elts	96	96
Center frequency (MHz)	7	6.5
Pitch (mm)	0.327	0.216
Elevation (mm)	4	5
R.O.C (mm)	60	10

Table 1 : Transducer arrays specifications.

Active material of both arrays is 1-3 piezocomposite [2], fabricated with the dice and fill technique, based on high dielectric permittivity piezoceramic filled with resin. The ceramic volume fraction is set to achieve a good trade-off between bulk damping, dielectric permittivity and coupling coefficient. The piezocomposite kerf is chosen in order to have lateral mode resonances far from the bandwidth of interest. The acoustic stacks are completed with 2 matching layers and a backing material made by mixing epoxy resins and inorganic or metallic powders.
The assembly of the different layers composing the acoustic stack is performed on the same rigid body that will maintain the geometric accuracy of the arrays and imaging planes: plane orthogonality, distance between arrays and tilt angle equal to 0° between the two curved linear arrays.
Connectivity between arrays and probe handle is provided by flexible circuits running along the probe shaft which allows minimum volume of interconnects. Flexs are ended by connectors that will be plugged to electronic boards integrating multiplexing electronics. Then a monolithic lens is moulded on the 3 arrays using RTV silicone with appropriate acoustic properties and radius of curvature to target specified focal distance. This concept of 3 arrays in one lens, provides the advantage of limiting bonding interfaces and thus increase waterproofness and dielectric strength of probe head. Finally the probe head is integrated and shielded in the probe housing, and sealed hermetically.

III. MULTIPLEXING ELECTRONICS AND SYSTEM FRONT-END CONNECTIVITY

In this probe, the main objective of integrating multiplexing electronics in the handle is to limit the number of coaxial cables to one third of the total active elements and to lower the number of active channels.
Another advantage of limiting the number of coaxial cables is to decrease probe weight and then to enhance the ergonomics. To implement the switching function, we used 16-channels high-voltage analog switch integrated circuits (ICs). The set of 16 analog switches are controlled by 1 input logic control. Specifications of these ICs switch contact are : Resistance = 22Ohms, Capacitance = 22pF and they have a max switching frequency of 50kHz that is far higher than what is needed for real time image switching. On the PCB (1 by array), 6 multiplexing ICs are soldered, with the capability to switch ON or OFF elements of the corresponding array to the cable. All logic signals of ICs are connected, thus with one TTL signal coming from system front-end it is possible to activate the desired array. The three boards are in parallel so with the 3 commands D1/D2/D3 : A1 or A2 or A3 array can be selected (Figure 2).
A common ground is applied to high voltage power supply, logic power supply and imaging signals. 3 types of power supplies are necessary for the electronics: -80V DC, +80 V DC and 5V DC; they are taken from the system front-end through the cable.

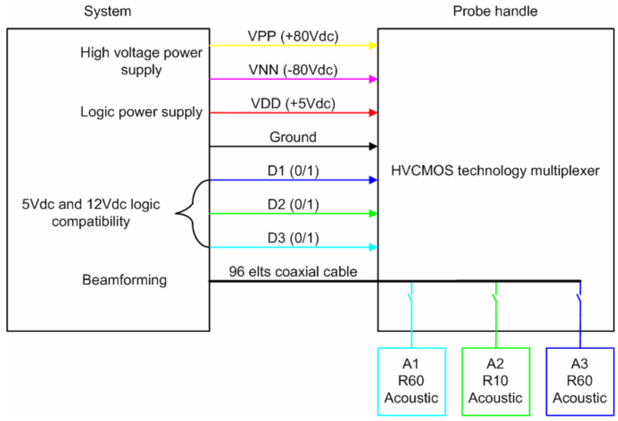

Figure 2 : Block diagram of multiplexing electronic and system front-end requirements

PCBs were designed with the objective to reduce the volume of the probe handle to endocavity probes standard.

IV. ELECTROACOUSTIC AND ACOUSTIC CHARACTERIZATION

First characterization step to evaluate integrated electronics impact and final probe performances is the measurement of homogeneity of electroacoustic performances. The arrays are immersed in water handled by a tilting – translating mechanical system. A 2.2m , 50Ω, 110pF/m, 96 elements coaxial cable is connected between the arrays (with or without electronics) and a 192 channels multiplexing electronics that allows the switching of excitation between the probe elements and the panametrics 5072PR pulser-receiver. This control electronics is equipped with DC supplies and logic signals to drive ICs in the probe handle. Arrays are positioned geometrically and acoustically in front of steel targets (curved one with 80mm radius of curvature for A1 & A3 and curved 30mm radius of curvature for A2). Then, all pulse-echo signals are acquired and stored. For the three arrays with and without ICs, we calculated all fundamentals electroacoustic parameters (center frequency, high and low cutoff frequencies, fractional bandwidth and pulse duration). We completed these measurements by a focal distance evaluation on flat-steel target for all arrays. Results are displayed in the table below.

	A1&A3		A2	
	Without ICs	With ICs	Without ICs	With IC:
Sensitivity (dB)	0	-1.9	0	-1.5
Fc (MHz) @-6dB	7.1	6.85	5.94	5.74
Axial Resolution @-20dB	202	205	204	216
Bandwidth @6dB (%)	66	64.5	78	75
Focal distance (mm)	20.5	20	19	17

Table 2 : Electroacoustic performances of arrays with and without ICs in the handle

First, we can observe a slight decrease of all arrays performances connected to ICs as compared to ones without. But this was predictable with the value of switch contact resistance (22 Ohms) that mismatches the element and the cable and then changes electric properties of signal path. But such low variation of performances will certainly not impact significantly the image quality of the probe. On the other hand when observing pulse-echo response of arrays elements on flat target (Figure 3), we detect no major modification of electroacoustic signature.

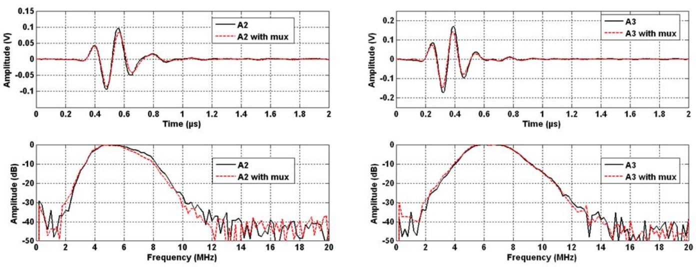

Figure 3 : Time response, frequency response of A2 (left) and A3 (right) central elements with and without multiplexing electronics at the focal distance in water on flat steel target.

Electroacoustic performances are not sufficient to confirm that ICs have no impact on arrays behavior, acoustic performances must also be evaluated. We measured then directivity pattern of arrays central elements in pulse-echo mode, at the focal point with a 6 mm diameter cylindrical target. Results of acceptance angle with and without ICs are displayed in the table and figure below

	A1&A3		A2	
	Without ICs	With ICs	Without ICs	With ICs
Peak-peak acceptance angel	41°	39°	30°	29°
Harmonic acceptance angle @ Fc	51°	49.5°	33°	32°

Table 3 : Acoustic performances of arrays with and without ICs in the handle

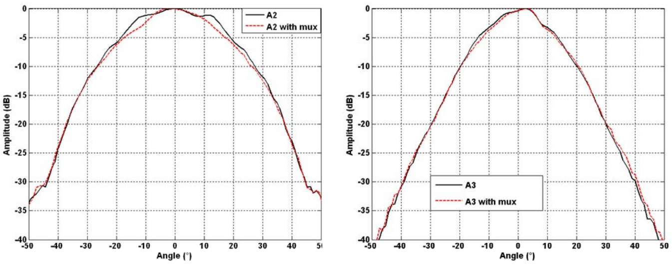

Figure 4 : Directivity pattern at focal point of A2 (left) and A3 (right) array without (solid line) and with (dashed line) ICs in the handle

As observed with the electroacoustic performances, the integration of multiplexing electronics does not decrease significantly array performances.

The previous results demonstrate that multiplexing arrays in the probe handle do not modify arrays acoustic behavior. No spurious modes or cross-coupling are observed on directivity pattern, thus we can expect that no discrepancies will appear on image.

V. CLINICAL EVALUATION

The clinical evaluation of the probe was performed on a 3G Ultrasound system (http://www.3gultrasound.com/) dedicated to brachytherapy protocol.

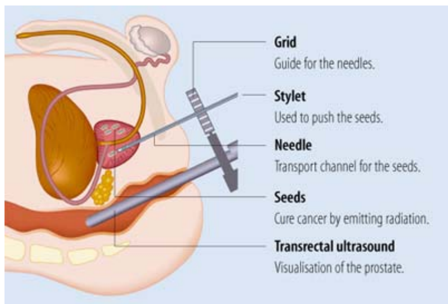

Figure 5 : Brachytherapy protocol, seeds placement with ultrasound imaging guidance

Brachytherapy uses ultrasound imaging to visualize the needles for accurate placement of small radioactive sources (seeds) directly into the prostate. Ultrasound imaging allows accurate planning, placement and implantation of the radiation sources. Implantation of the radioactive sources is a minimally invasive procedure, which can be performed in an outpatient setting. Radioactive seeds are inserted through the perineum skin (the area between the scrotum and the anus) into the prostate gland. With correct planning, the surgeon can implant the radiation sources for maximum benefits to effective cancer treatment.

This probe design, with the possibility of simultaneous visualization of transverse and longitudinal planes is a great advantage. As displayed on the image below, the grid for needle guidance can be easily visualized in the transverse image. The position of the needle tip is determined in the longitudinal image formed by the overlap of the two low curvature arrays images.

Image quality indicates that probes with ICs can reach high-end performances.

VI. CONCLUSION

In this work, we demonstrated that it is possible to integrate multiplexing electronics in a multiplane probe without decreasing electroacoustic and acoustic performances.

Very good image quality was obtained during endorectal imaging applied to brachytherapy. This multiplexing design was also applied successfully to biplane phased arrays and other types of multiplane probes. This technology is a good solution to provide low number active channels ultrasound systems with the capability to connect probes with higher number of active elements.

VII. ACKNOWLEDGMENTS

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Figure 6 : Clinical evaluation of Biplane probe