Introduction to Medical Imaging

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Medical Business Unit
Texas Instruments
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Agenda

• TI in Medical Market
• Ultrasound Imaging
  – Principles
  – System Considerations
• Other Imaging Modalities
  – X-ray Imaging
  – CT Imaging
• Medical Image Safety
TI in Medical Market
TI Commitment to Medical

Committed for the long term
• Dedicated Medical Business Unit (MBU) Organization combines expertise from Military/Automotive to support Medical customers with for enhanced products, quality and services.

Investing in Innovation
• R&D
• Venturing (funded)
• Partnering (co-marketing, design, etc)
• University Programs -$15M

Driving standards
• Continua Health Alliance (interoperable telehealth)
• IEEE-11073 (medical communication)
• iNEMI MCRS (medical component reliability)
TI Medical Organization

DSP
- High Performance Medical
- Low Power Medical

HPA
- Medical / High Rel
- Medical BU
- Analog Signal Chain
- Implantables
- Wireless Connectivity

Legal

Power

WW Strategic Marketing

RFID

MSP430

Regional Medical Champions

TI Proprietary – Strictly Confidential
TI Medical offering

- University research
- VC investment
- New technologies
- Implantables

- Application-specific products
- TI investments
- Dedicated resources

- Broad analog and digital catalog portfolio

Quality & reliability
Process technology
Sales & applications support

TI Proprietary – Strictly Confidential
Medical overview

Broadest portfolio of analog and embedded processing solutions in the market
Medical imaging modalities

- MRI
- Hyperspectral Imaging
- Ultrasound
- PET / CT / OCT
- Digital X-ray
- Vein viewer
# Complete IC portfolio for medical imaging

<table>
<thead>
<tr>
<th>Embedded processors</th>
<th>CT</th>
<th>Ultrasound</th>
<th>MRI</th>
<th>X-ray</th>
<th>PET</th>
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<th>MRI</th>
<th>X-ray</th>
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*high-performance DSPs include multi-core, single-core and floating point
Ultrasound
Overview of Ultrasound

• Ultrasound Basics
  – Advantages
    • Real-time & Non-invasive
    • Inexpensive
    • Multi-channel in a single system
    • Growing market of >4 billion worldwide
  – Operation Principles
    • Sound vs Ultrasound ~ 20Hz-20KHz vs 2-20MHz
    • Transducer ~ Loudspeaker & Microphone
    • US AFE ~ Power Amplifier & Signal Amplifier
    • US System ~ Radar System
Ultrasound Basics

- Imaging Modes
  - Brightness Mode (B-mode) 64-256 channels
  - Doppler Mode (D-mode) 1-64 channels
  - Color Doppler mode (2-D Doppler) 64-256 channels
  - 3D & 4D Ultrasound 1024-4096 channels
Ultrasound Basics

- Ultrasound Basics
  - Growing Portable Ultrasound Market
    - Ambulance, Emergency Room, Battle Field
  - Demand of Advanced ICs
    - Compact, Low Power, & Low Noise
    - More Channels per System
    - More Systems per Year
    - Much More Opportunities for ICs
Principle
The machine – Top level
## Physics (I)

### Attenuation in Imaging Systems for Medical Diagnostics - Siemens

<table>
<thead>
<tr>
<th>Substance</th>
<th>c [m/s]</th>
<th>$\rho$ [g/cm$^3$]</th>
<th>$Z = \rho c \times 10^5$ [Rayl]</th>
<th>Attenuation [dB/MHz.cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat</td>
<td>1470</td>
<td>0.97</td>
<td>1.42</td>
<td>0.5</td>
</tr>
<tr>
<td>Muscle</td>
<td>1568</td>
<td>1.04</td>
<td>1.63</td>
<td>2</td>
</tr>
<tr>
<td>Compact bone</td>
<td>3600</td>
<td>1.7</td>
<td>6.12</td>
<td>4-10</td>
</tr>
<tr>
<td>Air</td>
<td>331</td>
<td>0.0013</td>
<td>43.10$^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>

- **Position**
- **Frame rate**
- **Reflections**
- **Strong or weak**
- **Depth**
Physics (II)

\[ c = 1560 \text{m/s} \]

\[ R_{Axial} = \frac{\lambda}{2FBW} = \frac{c}{2} \tau_{-6dB} \propto \frac{c}{2f} \]

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>Wavelength [mm]</th>
<th>Penetration depth [cm]</th>
<th>Lateral resolution [mm]</th>
<th>Axial resolution [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.78</td>
<td>25</td>
<td>3</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>0.31</td>
<td>10</td>
<td>1.2</td>
<td>0.35</td>
</tr>
<tr>
<td>10</td>
<td>0.16</td>
<td>5</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>15</td>
<td>0.1</td>
<td>3.3</td>
<td>0.4</td>
<td>0.15</td>
</tr>
</tbody>
</table>

\[ f.2.x.\alpha = 100 \text{dB} \]

\[ \alpha = 1 \text{dB/(MHz.cm)} \]

\[ R_{Lateral} = \frac{c}{f} \frac{2r}{w \cos \theta} \]

Imaging Systems for Medical Diagnostics - Siemens
Frame rate

Example:

c = 1540m/s
60° sector
0.5° beam spacing
25cm depth

120 beams
25cm x 2 / 1540m/s = 320us / beam \{ 26 frames/s
Mechanical Scan

Probe Movement during Acquisition of volume

Central scan plane

Acoustic Window, Coupling fluid

Array

Gear

Motor

Position Sensing Device

Cables

Housing

Courtesy of GE

Mechanical

Electrical

Texas Instruments
Electronic scan

• Fast frame rate
• Low noise
• More patient friendly

http://www.es.oersted.dtu.dk/staff/jaj/field/index.html
Ultrasound System

TI Goal: More Colorful Diagram, ease of US design
Main Components in Ultrasound TX

- Ultrasound Transmitter: Signal Generator
- Ultrasound T/R Switch: Protect LV RX
- Ultrasound Multiplexer: Reduce TX/RX CH#
Main Components in Ultrasound RX

- **Ultrasound VCAs**
  - Amplify signals from 10uV~1V i.e. 100dB
  - Compensate attenuation in tissues

- **Ultrasound ADCs**
  - Digitize conditioned signals
Tx beamformer

Transducer array

1

2

3

4
Rx beamformer

Apodization

Delay

Transducer array
Receive Beamforming

Transducer array

ADC Sample Rate: 40MSPS→25ns interval
BF Resolution: <λ/16: 10MHz→>160MSPS→<5ns
Receiver Solutions for Ultrasound

System Channels
1024+

512
High End

512
AFE580X

256
AFE5805

AFE5804
Mid Range

128
AFE5801
AFE5851
Portable

64
Ultra Portable

32
Portable

Production
Sampling
Future

TEXAS INSTRUMENTS
Transmit Solutions for Ultrasound

Platform/System

<table>
<thead>
<tr>
<th>High End</th>
<th>Mid Range</th>
<th>Portable</th>
<th>Ultra Portable</th>
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- **TX734**: Quad Output +/-90V 3 Level
- **TX810**: 8 Channel TR Switch

Years:
- 2008
- 2009
- 2010

TI Proprietary – Strictly Confidential
Valuable Specs in Ultrasound

• Power/Noise
• Overload Recovery
  - Recovery time & recovery consistence.
  - Consistent recovery char leads to less color noise.
  - Overload recovery reports for AFE580x are available.
• Power up/down speed
  - Related to VCA shut down duration
  - Better power saving and more flexibilities for users
• Input Termination vs system performance
  - Active termination vs Passive termination
  - No external resistor needed for active termination
Valuable Specs in Ultrasound

- Matching among channels and chips
  - Considered probe sensitivity variation
  - Chip matching is a guaranteed number at ATE.
- Harmonic Distortion (HD2 and HD3)
  - Harmonic Imaging (HD2)
  - CW demodulation (HD3)
- Jitter vs Color Noise
- CW IQ Matching
  - Affect the forward and backward flow detection
- SNR at low gain i.e. SNR at near and mid range
  - Related to VCA IRN and PGA gain specs

Detail information can be obtained from TI MBU
Low Power/Low Noise for both ADC/AMP

<table>
<thead>
<tr>
<th>Bipolar Technology</th>
<th>CMOS Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW NOISE</td>
<td>LOWEST POWER LOGIC</td>
</tr>
<tr>
<td>WIDE DYNAMIC RANGE</td>
<td>HIGHEST LEVEL INTEGRATION</td>
</tr>
<tr>
<td>WIDE BANDWIDTH</td>
<td>SWITCHES, MUX’S and SAMPLE/HOLD’s</td>
</tr>
</tbody>
</table>

MOS at 2mA: 1.08nv/rtHz @ 500KHz
MOS at 3.5mA: 0.72nv/rtHz @ 500KHz
Bipolar at 2mA: 0.6nv/rtHz @ 500KHz
Low Power/Low Noise for both ADC/AMP

- **ADS528x-C05**
  - 0.18um CMOS
  - Low Power ADC
  - High Digital Intensity

- **VCA85xx –BiCom3X**
  - 0.35um BiCOMS
  - Lowest Power 60mW/Ch
  - Highly Integrated (8 Ch)
  - Voltage-Controlled AMP

- **BiCOM3x or Future BiCom Process**

- **Low Power Low Noise AFEs**

- **Ultrasound AFE: Lowest Noise for Superior Image Quality**

- **Texas Instruments**
Overload Recovery

• Signal Path & VCA Requirements

**Near Field**
- Low TGC Gain setting
- Large echo likely to overload LNA

**Mid-far Field**
- Increasing/High TGC Gain setting
- Potential overload of LNA and PGA

**Need:**
- Fast overload Recovery of LNA
- Fast and Repeatable overload recovery characteristics

- Multiple Echoes closely spaced together (wall,blood,wall)
- Large difference in strength (40~60dB)
Overload Recovery

- **AFE5805: Proof of zero phase shift**
  - PGA=30dB, Vcntl=1V, No Clamp, 15M LPF, Gain~45dB
  - Signals: 250mVpp/0.25mVpp

1. AFE5805 can detect signals with DR>60dB.
Overload Recovery

- **AFE5804: Proof of phase detection**

1. The small signal amplitude in No1-No2 is doubled.
2. 180 phase detection can be proved by amplitude doubling.
3. AFE5804 achieves excellent performance even at low power mode.
Gain Matching & Range

Dev-Dev Absolute Gain Matching
1200 units/ 9600 channels, Vcntl=0.8V

Mid Gain

Dev-Dev Absolute Gain Matching
1200 units/ 9600 channels, Vcntl=1V

High Gain

Dev-Dev Absolute Gain Matching
1200 units/ 9600 channels, Vcntl=0.1V

Low Gain
Termination for Ultrasound

• Termination Purpose
  – Ultrasound signal is a wide band signal → Short pulse
  – Resolution is depending on pulse length
  – Reflection can affect system resolution
  – Xducer/cable: 100ohm; Rin of AFE: 10K → Mismatching → Reflection
  – Termination → Reduce reflection → Improve Resolution

Reflection from mismatching
Ideal 0dB axial resolution
Degraded 0dB axial resolution due to mismatching

Courtesy of Biosound Inc
Termination for Ultrasound

- Termination Resistor is NOT noiseless
- Thermal Noise is Added
- Low Impedance termination → High Noise Figure
- Termination vs Noise Figure
  - No Termination: Lowest NF
  - Active Termination: Medium NF
  - Passive Termination: Highest NF
- Active termination is common on new AFEs
Future Ultrasound Solution

- Lower Power
- Higher Integration
- Ultra-Portable system
- Ultrasound Systems in Walmart
Digital X-rays
X-ray – Generation

Energy $\propto$ Voltage

Dose $\propto I$

Unfiltered in vacuum
K-shell characteristic radiation
Bremsstrahlung
Maximum photon energy
Photon energy

Courtesy of Siemens

Texas Instruments
X-ray Machine

Filter/collimator

Anti-scatter grid

TRANSMITTED

DETECTOR
X-ray imagers overview

**Indirect imaging**

- **Screen-Film System**
  - X-ray energy
  - Scintillator screen
  - Film
  - Scintillator screen
  - Laser
  - Signal profile

- **Computed Radiography**
  - X-ray energy
  - Photostimulable storage phosphor imaging plate
  - Imaging plate moved to reader
  - Storage phosphor imaging plate
  - Signal profile

- **CCD Detector with Scintillator Screen**
  - X-ray energy
  - Scintillator screen
  - Focusing Lenses
  - CCD Cameras
  - Signal profile

- **Scintillator (Phosphor or Cesium Iodide) with Photodiode Array**
  - X-ray energy
  - CsI (TI)
  - Photodiode array with a-Silicon Thin-Film Transistor (TFT) and storage capacitor
  - Signal profile

**Direct imaging**

- **Amorphous Selenium DirectRay® Detector**
  - X-ray energy
  - Field electrode
  - Dielectric layer
  - Semiconductor (a-Selenium)
  - Electrode collection array with a-Silicon Thin-Film Transistor (TFT) matrix and storage capacitor
  - Signal profile

*Courtesy of Hologic*
Digital advantages vs. Screen/Film

- Large dynamic range
- No films, chemicals
- Fully digital
- High DQE (Detective Quantum Efficiency)

Typical usage:
- 0.5 mAs (3200)
- 1 mAs (1500)
- 2 mAs (800)
- 4 mAs (400)
- 8 mAs (200)
- 16 mAs (100)
- 32 mAs (50)
- 63 mAs (25)

Under exposed

Over-exposed

Direct
Indirect

Scintillator

ADC

Readout

Addressing

AFE-XR0064 operation

1. CDS samples offset.
2. The panel control turns on the TFTs of a new column of pixels.
3. The charge is integrated (needs about 14us).
4. The CDS takes the integrated values and subtracts the offsets.
5. We can now RST the integrators. CDS still holds the analog values.
6. Analog values are muxed to the ADC inputs.
Readout time

Scan lines controlling gates of TFT:
- \( R_{on} \approx 1-2\, \text{M}\Omega \)
- \( C_{\text{pixel}} \approx 1-2\, \text{pF} \)

Example: 1536 * 1536 panel
Divide panel on 2 blocks of 768 columns, each with 24 AFEXR0064:
- \( 768 \times 27.8\, \text{us} = 21.35\, \text{ms} \to \text{FR} > 30\, \text{fps} \)

For 128 lines (1 pixel/line):
- \( T_{\text{min}} = 27.8\, \text{us} \)
- Fr > 30fps

142mW

130mW
Computer Tomography (CT)
The machine

3 revolutions per second
1000 profiles per revolution

3KSPS/pixel
Imaging the heart - Challenges

- @ 60bpm → 1 beat/s.
- Need 100ms shot at least to resolve 1mm in diastole (when heart is more still)
- Faster shot for other phases of the heart or better resolution (for plaque, smaller arteries…)
- 12cm long.
- Image the heart in one breath hold.
- Varying beats: % case with stable heart beat (courtesy of GE):
  - 4 beat: 97%
  - 5 beat: 92%
  - 8 beat: 39%
  - 10 beat: 10%
Imaging the heart - Technique

ECG synchronization
Switched Integrator

Photodiode Current

ADC

20bits

≈ 6KSPS (x2)

≈ 7mW/channel

DDC232

Switched Integrator

Photodiode Current

ADC

20bits

≈ 6KSPS (x2)

≈ 7mW/channel

DDC232

Switched Integrator

Photodiode Current

ADC

20bits

≈ 6KSPS (x2)

≈ 7mW/channel

DDC232
Medical Imaging Safety
Radiation

Natural background: 2.4mSv/year
Air travel crew: 3mSv/year
Radiation worker federal limit: 50mSv/year
Dental radiography: 0.01mSv
Chest radiography: 0.1mSv
Mammography: 0.7mSv
PET/SPECT: 7mSv
Chess CT: 8mSv
Pelvic/abdomen CT: 10mSv
CT Angiography: 15mSv
50% of cases die in 30 days: 3Sv
Thank You!!!
Comments & Questions😊
Backup: PET

Introduction to Medical Imaging
The machine
The detector

Example (from Derenzo): NaI(Tl) - 3.3 cm
Light output: 50k (38k?) photons/MeV
Principal Decay time: 230 ns
Index of refraction: 1.85

15000 photons at photocathode
3000 photoelectrons at first dynode
3.10^9 electrons at anode

1 to 10 = dynodes
11 = anode
F = focusing electrode
P = photocathode

Courtesy of Hamamatsu

RADIATION SOURCE
GAMMA RAY
REFLECTIVE COATING
OPTICAL COUPLING (USING SILICONE OIL)
SCINTILLATOR
PHOTO-ELECTRONS
To 11
To 3
To 9

RELATIVE RESPONSIVITY (AMBIENT CONDITIONS)
RELATIVE RESOLUTION (AMBIENT CONDITIONS)

10V DC
Centroid

To ADCs
Position
Anger logic

\[ X_m = \frac{\sum_{i} x_i E_{mi}}{\sum_{i} E_{mi}} \]
Front-end

\[ X_m = \frac{\sum x_i E_{mi}}{\sum E_{mi}} \]

\( 1/2 \) of ADS5273
12bit
70MSPS

Time Coincidence (TDC)

LVDS

DSP