Sensory functions in MDT therapeutic and diagnostic devices

Overview per business segment

Some specific in-vivo monitoring systems

General performance restrictions

An example of external monitoring: Atrial Fibrillation Alarm

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All of Medtronic Inc.
Sensor functions and applications in Medtronic devices (1)

- Cardiac Rhythm Management
- Closed-loop therapy (autonomous)
- Neuro, Diabetic, Gastro, ENT
- Minimally-invasive Surgery / Implant
- Cardiac Surgery
- Diagnostics and Monitoring
- Vascular
- Spine, Surgical Navigation

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Sensor functions and applications in closed-loop therapy (2)

EGM, Activity, OxygenSAT, Pressure
In Pacemakers and ICD’s

Closed-loop therapy (autonomous)

Minimally-invasive Surgery / Implant

Diagnostics and Monitoring

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Sensor functions and applications in Medtronic devices (3)

Physiological parameters
Pressure, Temperature, ECG, EGM
With catheters and leads

Closed-loop therapy
(autonomous)

Minimally-invasive
Surgery / Implant

Diagnostics and Monitoring
Sensor functions and applications in Medtronic devices (4)

- **Absolute pressure**
  - EGM, ECG
  - With Reveal, Chronicle

- **Glucose, pH**

- **Blood proteins**

- **ECG**

- **Closed-loop therapy**
  - (autonomous)

- **Minimally-invasive Surgery / Implant**

- **Diagnostics and Monitoring**
  - (IRM&CareLink investig.)

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Diagnostics and Monitoring: In Vivo Chronic

**Medtronic MiniMed**
Continuous Glucose Meas.

- Electrochemical sensor.
- Continuous, automatic monitoring of glucose in the subcutaneous tissue
- Reading stored every 5 min
- Sensor replaced every 3 days

**Others:**
GlucoWatch
Pelican Technologies, Advanced Biosensors
M-Biotech, Kivalco

Glucose Monitoring Systems, Start Up, Mar 2003
Diagnostics and Monitoring: In Vivo Chronic

Gastro-Esophageal Reflux Disease (GERD)  
Medtronic Gastro  
Bravo pH Monitoring

**pH Sensor**

- Gel-coated Antimony electrode and reference electrode
- Surface area of Antimony electrode determines output voltage (0 to 600 mV, pH 7-1, respectively)
- 61M+ Americans have reflux > 1 / mo
- 21M Americans have GERD

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Diagnostics and Monitoring: In Vivo Chronic

- Diagnostic for Unexplained Syncopy
- Offers up to 14 months of continuous, leadless ECG monitoring
  - Minimally invasive, outpatient procedure
- Patient activated and auto triggered to capture ECG
  - Programmable to store up to 42 minutes of ECG
- High diagnostic yield (55-88%)\(^1,2\)

Diagnostics and Monitoring: In Vivo Chronic

Diagnostic for Unexplained Syncopy: Insertable Loop Recorder

Cardiac Arrhythmias and Risk Stratification (CARISMA)

• Design
  – Multicenter study, Post-MI, Reveal Plus implanted
• Results
  – 29 patients met criteria; mean follow-up of 47 days
  – 6 patients with nonsustained VT (21%): ICDs implanted
  – 3 patients with 3rd degree AV block (11%): DC PMs implanted
• Clinically significant arrhythmias were observed early after acute MI in a high proportion of patients with depressed LVEF
• Study expanded to > 170 patients

www.medtronic.com
Diagnostics and Monitoring: In Vivo Chronic

Diagnostic for Unexplained Syncopy: Insertable Loop Recorder

Cardiovascular evaluation may identify an alternative diagnosis and should be considered early in the diagnostic process.

- Original Diagnosis: Treatment-Resistant Epilepsy (n=74)
  - No Change (n=43) 58%
  - Psychogenic (n=2) 2%
  - Cardiovascular (n=29) 40%

Diagnostics and Monitoring: In Vivo Chronic

Medtronic Chronicle®
Implantable Hemodynamic Monitor

- RV pressure sensor measures:
  - Systolic and diastolic pressure
  - Estimated pulmonary artery diastolic pressure
  - RV dp/dt (positive & negative)
- Heart rate & activity
- Core body temperature
- Continuous remote monitoring
- WW HF prevalence is 22.5M with 2M new cases per year. 80% are 65 years old or older

Source: New Medicine Reports 1997
1999 Heart and Stroke Statistical Update, AHA
In general, performance of sensory functions is determined by:

1. **Biostability and biocompatibility (2 days – lifelong)**

2. **Sensitivity and specificity**

3. **Power consumption** (2-50% is consumed by telemetry)

4. **Reproducibility** (implant site, manufacturing)

“The human body is the most hostile environment imaginable”
Monitoring ambulant patients for atrial fibrillation
Atrial Fibrillation

- Atrial Rate: > 300 bpm
- Rhythm: Irregular
- Ventricular Rate: Variable, depends on:
  - AV-node conduction properties
  - Sympathetic and parasympathetic tone
  - Drugs
- Recognition: Absence of P waves

Normal Sinus Rhythm

- Atrial/Ventricular Rate: 60-80 bpm
- Rhythm: Regular
- Recognition: Clear presence of P waves

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Go AS et al. JAMA 2001

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Percentage of Strokes Associated with Atrial Fibrillation$^{16}$

Age Group (Years)

<table>
<thead>
<tr>
<th>Age Group (Years)</th>
<th>Percentage of Strokes Associated with AF</th>
</tr>
</thead>
<tbody>
<tr>
<td>50-59</td>
<td>10%</td>
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<tr>
<td>60-69</td>
<td>20%</td>
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<tr>
<td>70-79</td>
<td>30%</td>
</tr>
<tr>
<td>80-89</td>
<td>40%</td>
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</tbody>
</table>

AF Alarm – Rational

Success in pharmacological cardioversion is limited, when Atrial Fibrillation is present for more than 6-10 hours.

More than 50% of patients do not feel reoccurrence of AF.

Detection of AF was only possible by intensive trans-telephonic monitoring.

A continuous worn external device providing an alarm upon reoccurrence of AF would increase success in pharmacological cardioversion, and decrease burden to the patient.

Storage of ECG strips around AF events enables later analysis.
Requirements

• Detection of Atrial Fibrillation
  – Fast detection (<10 min after onset of AF)
  – Accurate discrimination AF/NSR (Se > 90%, Sp > 90%)

• Storage of ECG/RR Episodes
  – Upon AF onset/termination (2 min pre / 2 min post event)
  – Patient triggered episodes

• Patient Wearable Device
  – Longevity (> 1 week of fullcharged batteryset)
  – Single lead ECG (3 electrodes)
  – Patient alarming function (Audible/visual)

• Physician interface
  – Stored ECG/RR retrieval (Host PC)
  – Status/Reconfiguration algorithms (Host PC)
Black Box Analysis

AF Alarm Device
(includes ECG electrodes, cables)

- RE
- LE
- Ref
- Patient Event
- AF alarm on/off
- Reconfiguration (Physician)
- Skin irritation
- EMI
- Low Battery
- Electrode dislodgement
- Movement artifacts
- Muscle artifacts
- Humidity
- Shock & Vibration
- Temperature
- EMI
- Skin irritation

AF alarm (audible)
AF alarm (visual)
ECG/RR
AF Markers
Status (physician)
Functional blocks

Analog Front End
- Instrumentation amplifier
- AC coupling
- R-wave filter
- Programmable Gain Amplifier (PGA)
- Level shift

Digital Front End
- AD Conversion

R-wave Detection
- Digital signal conditioning
- Peak detection
- Automatic Threshold Control (ATC)
- PGA control
- Signal loss detection

AF Detection
- Cluster Signature Metric (CSM)
- (RR Variability Meas.)
Front end

- ECG Amplifier
  - HV protection
  - AC Coupling (0.72 Hz)
  - Gain 32 dB

- Band Pass Filter
  - Pass-band
    - 5 Hz (24 dB/Oct)
    - 12 Hz (12 dB/Oct)
  - Constant group delay (Bessel)
  - Multiple feedback design

- PGA
  - Gain
    - 0.25, 0.5
    - 1, 2, 4, 8

- Level Shifter
  - $V_{ref}/2$

- ADC
  - Resolution 12 bit (unsigned)
  - Dynamic range $0 - V_{ref}$
  - Sampling Rate 200 Hz

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R-wave detection

ADC

LP Filter

HP Filter

d/dt

$X^2$

Moving Average

Peak Detector
R-wave detection

Threshold

P_n

P_n *K_1

P_n *K_2

P_{n+1}

P_{n+1} *K_1

P_{n+1} *K_2

A

B

C

D

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AF Detection based on RR variability

RR-interval sequence

Histogram
Range: –600 to +600 ms
Bin size: 30 ms (40 bins)
Episode Length: 2 min

AF Detection
AFScore > AFTreshold
Algorithm verification, using patient data

- Holter dataset
  - 50 patients (> 24 hrs recording each)
  - Fully annotated (Marquette Holter analysis system)
  - RR interval sequence, Raw ECG (20/50 patients, 3 leads)
  - Normal Sinus Rhythm (NSR)
  - Paroxysmal AF (PAF) / Chronic AF (CAF)

- Clinical feasibility
  - Age 33 – 87 yrs
  - 18 episodes PAF, 7 episodes NSR
Algorithm verification: PAF detection (1)
Algorithm verification: PAF detection (2)
Algorithm verification: CAF detection
Algorithm verification : Detection Results

- Total # of episodes (2 min) 33100
  - AF 10732
  - NSR 22386

- True positives / negatives 10391 / 21153
- False positives / negatives 1215 / 341

- Sensitivity / Specificity 96.8 / 94.5 %
## Algorithm verification: Detection Results

<table>
<thead>
<tr>
<th>Case</th>
<th>Patient</th>
<th>Position</th>
<th>Rhythm</th>
<th>AF</th>
<th>Detection</th>
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<td>+</td>
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<tr>
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<td>sit</td>
<td>PAF</td>
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<td>+</td>
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<tr>
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<td>CAF/SR(ECV)</td>
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</table>

- **23 Subjects**
  - Age 33 – 87 yrs
  - 18 episodes AF
  - 7 episodes NSR
- **Se / Sp = 89 / 86 %**
- **PPV / NPV = 94 / 75 %**
AF Alarm 09014 – Main components

MDD certified / self-CE marked
Not commercial distributed
AF Alarm 09014 – PC Software / screenshots

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