Neuronavigation, Stereotactic Neurosurgery

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DEFINITIONS

“Stereotactic” (Greek “stereos” - 3-dimensional; Latin “tactus” – to touch) – to touch the point in the space.

Navigation - targeting in space relative to known reference points.

Image-guided neurosurgery (neuronavigation, “frameless stereotaxy”) - operative technique by which correlation (co-registration) between imaging studies and operative field is provided.

Co-registration is the fundamental principle of stereotaxy!

STEREOTACTIC NEUROSURGERY - use of coordinate system to provide accurate navigation to point / region in space (e.g. deep brain structures) without direct visualization.

HISTORY

- 1908: Horsley and Clarke develop first apparatus for insertion of probes into the brain based upon Cartesian planes and bony landmarks; only used in primates.
- 1947: Spiegel and Wycis report first human use of stereotactic device - to perform minimally-invasive psychosurgery but first use was movement disorders.
- 1948: Leksell develops first arc-centered frame.
- 1957: Talairach publishes first atlas based upon ventriculography and intracranial brain landmarks rather than bony landmarks.
- 1986: Kelley develops frame-based system for eye-tracking of operative microscope.
- 1986: Roberts develops frameless acoustic-based system for tracking operative microscope.
- 1991: Bucholz developed the first prototype for frameless sonic navigation of tracking tools and instruments in human cranial surgery

- Soon after incorporated optical digitizers to reduce inaccuracies from sound echoes
INDICATIONS

1. Tumor (biopsy, resection, radiosurgery)
2. Epilepsy (structural & physiologic data, resection)
3. Treatment of functional abnormalities (movement disorders, pain conditions) – by lesioning or stimulation. see p. Op360 >>
4. Stereotactic (implantations) of neutral tissue, drug transplants, gene therapy.
5. Spine (instrumentation)
6. Ventricular catheterization (EVD / VP shunt placement)

STEREOTACTIC PROCEDURES

STRUCTURAL

- for structural lesions that can be detected on imaging study (tumors, abscesses, infections)
1. Biopsy (avoid vascular malformations and strokes!)
2. Stereotactically guided endoscopic / open craniotomies - removal / debulking of deep-seated lesions with minimal manipulation of overlying tissue.
3. Stereotactically guided intracerebral hematoma / abscess evacuation (esp. deep-seated and multiple).
4. Interventricular / intracavitary irradiation see p. Rs11 >>
5. Radiosurgery (application of stereotactic principles to convergent beam-irradiating irradiation therapy) – see p. Rs11 >>

FUNCTIONAL

- changes function by altering aspect of abnormal functioning circuit (which may be upstream or downstream from pathologically affected part of circuit).
  • indications: movement disorders, pain, epilepsy.
  • target is usually anatomically defined and requires precise localization by brain atlases, in coordination with patient's own anatomy. see p. Op360 >>

Destructive methods:
- a) radiofrequency heat lesions - easiest to grade (temperature control of electrode tip);
- temporary lesions can also be produced prior to causing permanent damage to brain
- b) laser heat lesions
- c) mechanical lesions (with small wire loop)
- d) freeze lesions (cysteolyses using liquid N2)
- e) balloon lesions (to percutse surrounding brain on inflation)
- f) chemical lesions.

Augmentative methods – chronic brain stimulation, cell or tissue transplants, gene transfer.

IMAGING REQUIREMENTS

Following image types are supported by current software:
- CT, CTA
- MRI, MRA
- IML, DTI
- PET

“Stealth protocol”
- 1. 1-3 mm slice thickness
- 2. Volumetric (3D) scan – contiguous slices (e.g. T1 MPRAGE, CUBE FLAIR)
- 3. “Zero gantry” - zero tilt – not a requirement for modern navigation software
- 4. Request not to “cut” the nose and top of head

Patient with suspected tumor on plain hCT – order diagnostic+Stealth MRI – will save time and trouble!

Obtain CD from radiology and upload to the navigation station the night before surgery:
1) correct patient
2) correct study

TARGET LOCALIZATION

- see p. Op360 >>
A. Direct - target visually chosen from scan
B. Indirect - based upon position of AC-PC

TRAJECTORY PLANNING

- see p. Op360 >>

FRAME-BASED STEREOTAXIS

- uses stereotactic frame rigidly attached to skull.
  • most commonly used stereotactic frames:
    1) Brown-Roberts-Wells
    2) Cosman-Roberts-Wells
    3) Leksell Model G
    4) Radionics
    5) Talairach

  • frame is applied directly to skull (under local anesthesia) by four threaded pins that penetrate only outer table of skull – FRAME BOX is attached to frame – imaging to align brain, lesion, and stereotactic frame → TRAJECTORY PLANNING >> stereotactic arc is mounted on frame → biopsy
  *See below>>

  • frame is applied parallel to orbito-meatal line (approximately parallel to anterior commissure-posterior commissure (AC-PC) line).

LOCALIZING BOX is most accurate method of localization; it is scanner-independent and computer-assisted.
- localizing box with three sets of vertical and diagonal fiducial rods in N configuration is attached to base ring → scanning.
- CT-compatible localizer (left) and MRI-compatible localizer (right)
- in resulting image, rods are seen as dots.

- $z$ coordinate is obtained by determining position of each diagonal rod image in relation to its adjacent vertical rods; three such sets of vertical and diagonal rods determine three points in stereotactic space and define plane of target point.

- $x, y$ coordinates of each of nine rods are entered into computer, which calculates distance from each of three diagonal rods to base ring, based on proportionate distance of each diagonal rod from its associated vertical rods in that plane; these three points define target plane relative to base ring, and from this 3D coordinates of target are calculated.

- N.B. coordinates are referable to stereotactic base ring.

- lateral ($x$) measurements are denoted "left", "right +";

- AP ($y$) measurements are denoted "anterior +" or "posterior -";

- vertical ($z$) measurements are denoted "superior +" or "inferior -".

- because of variability of patient positioning in stereotactic instrument, isocenter of three orthogonal planes of stereotactic space will rarely superimpose upon intersection of corresponding intracranial planes as depicted in human stereotactic brain atlases.
**ARC-CENTERING ARC-RADIUS STEREOTAXIC INSTRUMENT** (Cosman-Roberts-Wells [CRW] instrument, LeKsell apparatus)

- Fiducials are reference markers (stickers, bone screws) which are fixed directly to the patient prior to imaging. Fiducial marks (skin staples, pins attached to skull) or custom fiducial marks (skin staples, pins attached to skull) can be moved to any position along arc; fiducial marks are aligned with actual patient (as digitized) with computer representation obtained from radiologic images.

- fiducial marks are fixed directly to the patient prior to imaging. Fiducial marks (skin staples, pins attached to skull) or custom fiducial marks (skin staples, pins attached to skull) can be moved to any position along arc.

- N.B. without rigidly attached frame, surgeon no longer has to deal with physical obstruction of sight device (such as video camera or sound waves).


**FRAMELESS STEREOTAXIS**

- rendering of scans (CT / MRI) into 3D images → rendered view of patient is aligned with actual patient using 3D digitizer, once patient is fixed in constant orientation in operating room.

- digitization can be performed using either fiducial marks (skin staples, pins attached to skull) or scalp-face surface - computer aligns actual patient (as digitized) with computer representation obtained from radiologic images.

- digitization can be performed by: a) mechanical device (such as sensor arm similar to that used in robotics) b) line-of-sight device (such as video camera or sound waves).

- brain warping may occur (e.g. following opening of skull, CSF leakage, partial tumor excision) → affected accuracy of device; H: brain updating (such as 3D ultrasound).

- N.B. without rigidly attached frame, surgeon no longer has to deal with physical obstruction from frame (e.g. turning craniotomy flap), but there may be sacrifice in accuracy - biopsy of small tumors, lesions for movement disorder still require stability and accuracy of frame!

- frameless stereotaxy in DBS - see below.

**FIDUCIALS**

- **Fiducia** (Latin “fiducia” – trust) - point of reference that can be visualized on imaging and identified on the patient by the surgeon and/or software package
  - Frame-based stereotaxy: Fiducials are bars built into cage or box that sits on frame during imaging.
  - Frameless stereotaxy: Fiducials are reference markers (stickers, bone screws) which are fixed directly to the patient prior to imaging.

**ROBOTICS**

- repositioning device or arc system with robotic arm.
  - instead of transferring 3D stereotactic target coordinates to arc system, computer calculates these coordinates and transfers them to robotic arm.

- special computer software is used to translate target and entry-point data into angular settings for each of moving joints of robotic arm, and it also programs depth of probe penetration.

- each of joints of robotic arm contains servomotor; servomotor houses optical incremental encoder, which provides position and velocity feedback to robot servosystem - position of probe tip can be displayed relative to lesion on operating room computer monitor in real-time.

- robotic arm is mounted to stereotactic base ring (fixed to patient's head) - base of stereotactic system, as in standard stereotactic systems).

- custom-designed probe holder is attached to robotic arm and allows for intraoperative fine adjustment of probe position.

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**STICKER FIDUCIALS**

- Timing Fiducials tend to fall off - apply them temporarily as close to the MRI as possible. And schedule MRI as close to surgery as radiology agrees.

- Location
  - first know where tumor is and think about position during surgery (supine, prone, decubitus) – fiducials must be accessible for registration after patient is positioned
  - apply most densely above tumor (i.e. center of fiducial configuration close to the region of interest) - error increases as the distance of the target from the fiducial centroid increases.
it is essential for the fiducials to define the sphere of the head - spread out fiducials across patient’s head (error increases as configuration of fiducials becomes smaller)  
- avoid linear fiducial configurations  
- spread markers asymmetrically  
- apply on nonmovable skin  
- avoid distorted scalp (thus, avoid occipital region)

Number:
- use as many fiducials as reasonably possible (minimum 3)  
- accuracy of targeting is increased by number of fiducials

### Fiducials

<table>
<thead>
<tr>
<th>n</th>
<th>attachment pattern</th>
<th>Imaging</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>95th percentile</th>
<th>Maximum</th>
<th>Steinmeier et al, 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>generalized</td>
<td>MR</td>
<td>2.45</td>
<td>0.94</td>
<td>2.3</td>
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<td>MR</td>
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<td>MR</td>
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<td>0.68</td>
<td>1.9</td>
<td>3.1</td>
<td>3.85</td>
<td></td>
</tr>
</tbody>
</table>

Technique:
- shave damn hair well!  
- clean scalp skin with alcohol  
- place fiducial  
- mark scalp skin at fiducial site - circle with permanent skin marker + mark the center dot  
- unapproved at VCU (worked well at VA): Dermabond those “lifesavers” to the scalp (so confused patient does not eat them all overnight).

**Bone Fiducials**
Rigidly attached to skull bone – highest accuracy; can be used for navigation in awake patients (vs. Mayfield skull clamp).

**PATIENT REGISTRATION**
Make sure reference frame (Stealth) / tracker (Stryker) is rigidly attached to skull clamp:
MANUAL REGISTRATION

1. **Point registration**:
   a. **Touch-n-Go (Stealth)** - centers of fiducial markers
   b. **Point Merge (Stealth)** - anatomical landmarks (can be used as rescue if during surgery registration is lost):
      - teeth ("bone fiducials")
      - nose tip
      - lateral canthus
      - nasion
      - tragus (mark slightly medial on scan as operator tend to push inwards with probe)
      - intersection points of bone sutures
      - old bur holes

2. **Surface matching (tracing)**
   - avoid one plane / one sphere
   - cover prominent areas such as orbit and nose
   - do not depress the skin when tracing

AUTOMATIC REGISTRATION

1. **Mask registration** (Stryker) - automatic touchless registration - enabling pinless procedures (if mask can be left on and visible to camera through transparent drapes)

2. **O-arm registration** - very high accuracy; ideal for patient in prone position (otherwise, difficult to register by any other method)

In *Stealth*:
- choose special module from the beginning ("O-arm tumor resection" or "O-arm biopsy")
- use radiolucent Mayfield (conventional Mayfield is also acceptable but has bulky lower part); attach Stealth "dogbone" from outside (and Mayfield bed attachment from inside) of Mayfield
- O-arm gantry cannot tilt more than 20 degrees.
- go to "Acquire scans" step → scan mode: high-resolution, medium-energy (no need for enhanced scan) → wait until scan is transferred → click "Stealth Merge" → select (on left side) the new scan to add to the right window (of scans to be merged) → click "Merge" *(do not make it as a new reference scan (leave old reference scan in place))

NAVIGATION ACCURACY

Acceptable ≤ 0.3 mm (in DBS ≤ 0.2 mm)

Clinical application accuracy (comparing seven registration methods):
### SOURCES OF ERROR

#### Imaging data set resolution
- e.g., slice thickness

<table>
<thead>
<tr>
<th>CT Slice Thickness (mm)</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0 ± 0.10</td>
</tr>
<tr>
<td>1.5</td>
<td>1.0 ± 0.15</td>
</tr>
<tr>
<td>1.8</td>
<td>1.0 ± 0.15</td>
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<tr>
<td>2.0</td>
<td>1.0 ± 0.15</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0 ± 0.15</td>
</tr>
</tbody>
</table>

**Note:** The large number of measurements yielded small standard errors of the mean and a resultant high confidence in those experimentally discerned means being representative of the true means of application accuracy for three tomographic frame systems. Mean standard error of the mean, N/A, not available; CT, computed tomography; BH, Brown-Roberts-Wells; OR, C-arm; Stealth, C-arm; N/A, confidence interval.

Maciunas et al., 1994

#### Imaging errors due to distortion
- MRI Image Distortion — magnetic field inhomogeneities and non-linear magnetic field gradients
  - Often worst in **coronal sections**.

#### Fiducial displacement

- Registration process (image-OR space)
  - Be very careful to ensure proper image R-L orientation (opposite of conventional CT/MRI orientation)

- Bent handheld probe
  - Navigation tool verification — system verifies that instrument is not bent.

- Target shift during resective surgery.

#### Prolonged time
- After registration there is ongoing silent loss of neuronavigation accuracy; major factors:
  1. Draping
  2. Attachment of skin-retractors
  3. Duration of surgery (target registration error was 1.3 mm after 30 minutes and increased up to 4.4 mm after 5.5 hours of surgery).

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### MEDTRONIC STEALTH

Stealth S7

Stealth TREON
Vertek – flexible arm that attaches to Mayfield frame.

Select CD type to upload:
- **Structured DICOM** – first choice; if struggles → choose **Unstructured DICOM** – always works but takes longer (system checks all possible modalities).

### SYNERGY CRANIAL

At the login screen, click **Cranial**.
Select **Standard Profile** or select a primary surgeon.
- you may add or customize surgeon profiles by clicking **[Add or Remove Surgeon]**
- surgeon profiles allow you to save surgeon-specific preferences (instruments, navigation options, view settings).

May navigate between several steps faster by clicking on it:

![Synergy Cranial Navigation Steps](image)

May use:

#### IMAGE management

One of three standard methods to import a new exam:
- a) **CD/DVD-ROM**
- b) **USB**
- c) **DICOM** - push exam across DICOM network (**exam automatically appears in the list of imported exams**) or click **[DICOM Q/R]**

Use volumetric (3D) exam for registration (most commonly T1)

1. Select **Patient task**, **Exams column**: select exam with **3D Objects** → **[Exam Details]** → **Modality drop-down list**: select “Object” (as new image type) - this automatically sets the colormap to Rainbow to match StealthViz colors and makes black background areas transparent.
2. **[StealthMerge]** → **[Start Merge]**: because the StealthViz exams were already merged in StealthViz, click **[Stop AutoMerge]** and **[Reset Merge]**.
3. Click the Pre-Merged Exams tab.
4. Verify the merge accuracy by clicking **Blend or Split-window**:
   a. If merge is accurate, click **[Verify Merge]**.
   b. If merge is not aligned correctly, click **[Cancel]** to cancel merge and proceed to plan and navigate on Hybrid exam. Alternatively, go back to StealthViz, recheck your work there (e.g., make sure Primary exam is one that was used as Reference for coregistration step), re-export exams, re-import them into Synergy Cranial, and use **[StealthMerge]** again.
5. When you have verified all exams, click **[Done]**.
6. In **PLAN task**: click **[Edit 3D Model]** or **[Build 3D Model]** → at the bottom left, select **[Import Models]** → select your StealthViz Objects → **[Import Models]**.

### REFERENCE SYSTEMS

#### OPTICAL
- A. **Mayfield frame + small passive cranial frame** (“blue butterfly”)
- B. **Neuro FrameLock** – skull mounted (requires separate incision) – for awake craniotomies to avoid pinning
AxilEM – do not need pinning (good for awake procedures); at VCU currently available only on Stealth #2 machine.

A. Skin “sticker” – use Mastisol then tape to skin; use nonmovable skin regions.

B. AxilEM Skull Mounted Tumor Resection kit – skull mounted (requires separate incision)
   - place Mobile Emitter in the special version of Vertek® Articulating Arm
   - no metal objects in the navigation field! (if metallic distortion causes excessive error, navigation will be disabled)
   - shunt passer has sensors at the stylet tip – uses real time navigation!

PLANNING

   - when tracing tumor projection on the scalp (to plan incision), use trajectory views (vs. anatomic orthogonal) – give the best view of tumor!!!

STEALTHVIZ

- see >>

FRAME LINK

- see p. Op360 >>

STRYKER

Manuals
- Stryker - Intellect Cranial navigation >>
- Stryker - CranialMap >>
- Intellect Cranial module

Dr. Graham uses mask registration before pinning in Mayfield; before pinning also register “rescue points”; after pinning, attach tracking device on arm on Mayfield, “transfer registration”, and recheck “rescue points”; remove mask.

TRACKING DEVICE
(analog to Medtronic SureTrak)
Calibration “pineapple”
Viktor's Notes℠ for the Neurosurgery Resident
Please visit website at www.NeurosurgeryResident.net