Incorporation of Imaging-Based Functional Assessment Procedures into the DICOM Standard
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I. Purpose

Drawing from the profile development of the QIBA-fMRI Technical Committee, the purpose of the QIBA-fMRI DICOM Subcommittee is to develop DICOM extensions supporting imaging-based functional assessment, specifically functional MRI (fMRI).

This working paper is intended to capture the concepts surrounding task-based fMRI, generalizing from the shared clinical and research experience of the QIBA-fMRI. Secondarily it should support other functional imaging studies (e.g. connectivity analysis) and other modalities (e.g. MEG). The level of detail should be sufficient to permit creation of DICOM object and relationship definitions as well as procedure steps describing the workflow, inputs, and outputs of functional assessment with imaging.

II. Background

As previously described [1], the fMRI workflow consist of multiple steps surrounding the actual imaging component, involving roles of patient, trainer, tester, processor and clinical user. Ultimately, we would like to capture both the steps of the workflow and the data items themselves in the DICOM framework.

1. Imaging-based functional assessment refers to the measurement of cortical activation resulting from a) extrinsic, functional tasks or b) spontaneous intrinsic functional ~~connectivity~~activation (‘resting state’).

2. Although fMRI based on blood oxygen level dependence (BOLD) is the focus of the QIBA-fMRI committee, assessment of cortical activation may be performed with other imaging sequences and modalities (e.g., MEG). Therefore, in striving to define the most generally useful DICOM extensions, we will strive to avoid terminology specific to a given imaging method.

3. Some of the familiar terms of fMRI will appear to be missing, e.g., ‘block paradigm,’ ‘event-related.’ The proposed presentation model scheme is intended to support fixed or randomized timing and stimulus selection, hence a superset of current methods. Phases can represent classic stimulus/control or periods in which stimulus events of a given class are scheduled to happen.

4. The framework must encompass all information necessary to analyze the imaging results of a functional assessment (stimulus, timing, analysis model, etc.). We choose to expand the scope to include information to meet other needs, e.g. audit logging,

[1] http://qibawiki.rsna.org/images/7/7a/DrTuckerSlides_2010_11_WG16.ppt_-Compatibility_M.pdf

reimbursement documentation.

DICOM coding is not a 'presentation language' but a means of promoting interoperability among imaging, processing and PACS systems. Expression of functional assessment explicitly in DICOM terms is intended to validate the proposal, not suggest that paradigms will be 'written' in DICOM.

III. Framework

The following is an outline of the major proposed records and data objects. These would translate to DICOM entities. See Dictionary below for more details. This framework will be supplemented by entity relationship graphs in the style of the DICOM standard.

The framework is divided into three high-level records: *Specification* for a paradigm, *Execution* of the paradigm Specification, and *Analysis* of a paradigm Execution. In terms of procedures steps, the training and testing (imaging) of a patient would be driven by the Specification and create one (or more) Execution records; the post-processing and derivation of a clinical report would in turn be driven by the Specification and Execution records, and result in an Analysis record.

Most stimulus 'files' (e.g. JPG) may be mapped to existing DICOM object types; alternatively, file system paths to external files can be employed. Stimuli will be DICOM object instances, identified via UIDs. At this time many data formats are left unspecified. In some cases they may map to existing DICOM records and tags created for other purposes. ~~Before getting too far into those details, would be best to~~

1. Paradigm Specification

a. Identification

   i. Title: Text description
   ii. Class (one of): Motor, Hearing, Vision, Language, Cognitive, Memory, etc.
   iii. Difficulty (one of): Nominal, Fast/Hard, Slow/Easy, etc.
   iv. Natural Language: English, etc.
   v. Author
   vi. Creation date
   vii. Revision

b. Imaging Model

   i. Modality & scan type

   ii. Scan length
   iii. Scan parameters
c. Statistical Model
   i. Relates epoch phases to expected cortical activation time course
d. Stimulus Set(s), each a set of Stimulus Objects, as follows:
   i. Stimulus file UID
   ii. Type (one of): Image (JPG, PNG, etc.), Movie (MP4, etc.), Sound (WAV), text (TXT), etc. Note that this may be defined by the UID above.
   iii. Inherent length (msec); either presentation time (stimulus file length if applicable) or zero to represent indefinite, continuous performance
   iv. Response(s) expected (multiple allowed):
      1. Response window [msec post-start, msec post-end]
      2. Response period length, msec
      3. Response Type (one of): key-press, eye tracking, physiological change, etc.
      4. Expected Response Value
e. Presentation model
   i. Instructions to Tester
   ii. Instructions to Subject
   iii. Timer definition(s)
   iv. Selector definition(s)
   v. Timeline, consisting of multiple Epochs, each defined as:
      1. Phase (one of): Stimulus/Control, A/B/C…
      2. Epoch length, msec
      3. ~~Stimulus~~ Presentation Pattern(s), one or more, each containing:
         a. List of one or more fixed-timing Stimulus Object UID(s)

            or

         b. Variable presentation: a Stimulus Set, chosen *from* using Selector, with timing determined by a Timer

2. Paradigm Execution
    a. Patient
    b. Ordering clinician
    c. Performing clinician (radiologist, neuropsychologist, etc.)
    d. Training/Testing Staff (technologist or clinician)
    e. Paradigm Specification instance UID
    f. Use (Training, Test, Re-test)
    g. Paradigm Execution for Training, Instance UID
    (if Test or Re-test, the record of the corresponding Training)
    h. Patient Record Attachments
    (other test results, e.g. handedness survey, neuro evaluation, etc.)
    i. System QA (equipment checklist, scanner QA, etc.)
    j. Staff comments & instructions
    k. Assessment of Patient performance by Staff
    l. Self-assessment of performance by Patient
    m. Assessment of paradigm execution
        i. Probably embeds limitations of the methodology (e.g. BOLD signal response versus MEG) and the physical implementation (e.g. visual frame rate, audio frequency range, etc.)
    n. Epochs performed, series of
        i. Timestamp
        ii. Phase
    o. Stimuli presented, series of
        i. Timestamp
        ii. Stimulus Object UID
        iii. Stimulus presentation length, msec
    p. Responses received, series of
        i. Timestamp
        ii. Type
        iii. Value
    q. Performance Metric (multiple allowed)

i. Title

ii. Type (e.g. attention probe, response accuracy, post-test memory, etc.)

iii. Number of trials

iv. Number of correct trials

v. Response Accuracy

~~v.~~vi. Response Latency

3. Paradigm Analysis

a. Paradigm Execution for testing, Instance UID

b. Paradigm Execution for training, Instance UID
(might be optional)

c. Processing Staff (technologist or clinician)

d. Epoch Evaluation (time-series editing)

i. Epoch timestamp

ii. Phase

iii. Disposition (one of)

1. Analyzed

2. Rejected (reason)

e. Imaging distortion correction

i. EPI – susceptibility, eddy currents

~~iv.~~ii. BOLD effect – neurovascular uncoupling (NVU)
Perfusion mapping, cardiovascular reactivity, etc,

~~e.~~f. Motion correction

i. Algorithm

ii. Results
E.g. statistics; time course of deviation removed in multiple translations & rotations

~~f.~~g. Statistical model applied

i. Ideal time course, this test instance
This may include reference waveforms

ii. Activation response model(s)
BOLD effect – hemodynamic response model
MEG – volume conduction models

- ~~i.~~iii. Analytical model, e.g. GLM, ICA and associated setup

~~g.~~h. Processed results: Activation time course

- i. Sampling volume method (e.g. strongest cluster, atlas segmentation, hand-drawn VOI)
- ii. Sampling volume description (3D mask)
- iii. Activation curve

~~h.~~i. Processed results: Map (multiple); each is an image series

- i. Type (one of)
  1. Functional activation, statistical parameter (e.g. t, r, F)
  2. Functional activation, AMPL
  3. Cardiovascular reactivity
  4. Functional connectivity (a/k/a resting state)
  5. other.
- ii. Parametric Threshold
- iii. Spatial Filtering applied
- iv. Clustering applied
- v. Color palette (applied or suggested)
- vi. Other features

~~i.~~j. Processed results: Contrast-Noise map

~~j.~~k. Processed results: Sample image volume from pre-processed time series

~~k.~~l. Processed results: Performance Metric (multiple allowed)

- i. Title
- ii. Type (e.g. attention probe, response accuracy, post-test memory, etc.)
- iii. Number of trials
- iv. Number of correct trials
- v. Response Accuracy
- ~~v.~~vi. Response Latency

~~l.~~m. Processed results: Other analyses

- i. Laterality

IV. Dictionary

This informal description would be supplemented by a dictionary of DICOM tags and records. Presently this is offered in order of appearance in the above framework.

Elements not listed here such as Patient, Ordering Clinician, Timestamp, image data, etc. are assumed to align with DICOM objects already available in the specification.

1. Paradigm: An assessment task, in which stimuli and tasks are related to cortical activation.

2. Paradigm Specification: A model for a functional paradigm, composed of a statistical model relating the paradigm task to cortical activation, stimuli employed, and a presentation model scheduling stimuli and expected responses through time.

3. Paradigm Execution: A record of the execution of a paradigm, including a timeline of the actual stimuli presented, responses elicited, and other observations about the run. This may be captured for training and testing (scanning).

4. Paradigm Analysis: A record of the analysis of Paradigm Execution results, including processing steps and results (e.g. motion correction), QA measures (e.g. epoch editing), activation maps, select activation time course(s), etc.

5. Stimulus: Digital representation of audio, visual, tactile etc. information delivered to the subject during the course of a paradigm.

6. Stimulus Object: A particular stimulus (either in DICOM format or as a file system path to an external file), along with some properties. Properties include type (image (JPG, PNG, etc.), audio (WAV), tone, movie (MPG), text, etc.); presentation length (inherent length of audio and movie files, or the specified time for text, images, tones, etc.); and expected response(s) and window for response.

7. Stimulus Set: An ordered collection of stimulus objects of the same type sharing one or more characteristics (e.g., a set of 'Famous Faces').

8. Timer: Specification for determining stimulus presentation timing. Timers can be reused multiple times in a paradigm execution, either restarting to reuse the same timing, or continuing a timing sequence.

    a. Mode:
    FIXED: specified msec of presentation.
    RANDOM: [min max] *msec*, seed:
    A pseudo-random uniform distribution (random characteristics, but guaranteed to produce the same sequence from a given seed). Timers are abstracted from

the presentation model itself so they may be used multiple times in a paradigm execution (e.g., to match the timing of faces in a stimulus epoch to the matched non-faces in a control epoch).

9. Selector: Specification for choosing a sequence of ~~selection indices from a range (1…n) corresponding to entries in~~ stimulus instances from a stimulus set. The selector is used to choose a particular subset of stimuli from a Stimulus Set, and defines their order of presentation. Selectors can be ~~reused~~ referenced multiple times in a paradigm execution, either restarting to reuse the same selection, or continuing a selection.

    a. Mode:
    LINEAR: start, end, increment (+/-), Stimulus-set
    This results in a sequence of selection from Stimulus-set beginning with the 'start' item, using every 'increment' item, until 'end.' Omitting start, end and increment results in the sequence of every item in the Stimulus-set.

    ~~RANDOM-REPLACEMENT: [min max] indices, seed, or~~
    RANDOM-REPLACEMENT: seed, Stimulus-set~~, or~~
    ~~RANDOM-NO-REPLACEMENT: [min max] indices, seed:~~
    RANDOM-NO-REPLACEMENT: seed, Stimulus-set~~, or~~
    A pseudo-random uniform distribution (random characteristics, but guaranteed to produce the same sequence of indices from a given seed). Selectors are abstracted from the presentation model itself so the may be used multiple times in a paradigm (e.g., to select stimuli paired in multiple classes, such as 'Face normal versus 'Face scrambled'). Selection without replacement prevents duplicate use of a given stimulus until the Selector is reset.
    The resulting sequence is distributed over a Stimulus-set

    b. Control:
    This is a tag used with references to a instance of the selector:
    START: Initialize the sequence, reference the UID of the first selected object;
    NEXT: Advance the sequence, reference the UID of the next selected object;
    REPEAT: Advance the sequence repeatedly, returning UIDs of remaining selected objects (NOTE: for brevity, REPEAT implies START as the first reference to a sequence);
    SAME: Reference the last selected UID again.

10. Timeline: The part of the presentation model defining the series of epochs making up the assessment. It is assumed that epochs are of predefined (though not necessarily equal) length, since they usually must be tied to the scan sequence of the imager.

11. Epoch: A period of time in the presentation corresponding to a particular phase of activation (e.g. movement versus no movement, or visual language versus aural language). During the epoch, one or more stimulus patterns are followed to elicit the desired activation. Multiple patterns might be executed in parallel during the epoch (e.g. supporting multi-media stimulation).

12. Stimulus pattern: A script for stimulus presentation composed of a Timer defining the start of each stimulus event, a Selector choosing the Stimulus Object to present in the event, and a Stimulus Set from which the Stimulus Object is selected.

13. Event: Logging of something that happened during the actual execution of a paradigm, consisting of a timestamp, event type, and the event details.

14. Epoch Event: Start of an epoch, logged in the Execution of the paradigm.

15. Stimulus Event: Event corresponding to presentation of a stimulus, including a timestamp, the UID of the stimulus object, and the actual presentation length.

16. Response Event: Event corresponding to a patient response during stimulus presentation, including a timestamp, response type, and response value. If the paradigm execution system supports it, the stimulus object whose window the response falls in may be recorded as well.

17. Performance Metric: Real-time measurement of patient performance during paradigm execution. Some presentation systems may analyze patient performance as the paradigm is executed (e.g. real-time accuracy in answering questions), but since all results are captured this could also be analyzed retrospectively. Hence it appears under both the Execution and Analysis records.

V. Implementation issues

There are many details concerning paradigm execution and analysis that generally elude the standards writers. In general, validation of paradigm design will be beyond the scope of DICOM. However, this is a list for discussion.

1. Stimulus specification: This is a slightly unusual DICOM 'instance' in that it exists prior to association with a particular patient. This may be merely a terminology issue; Color Palettes are presumably in a similar state, existing independently of a particular image instance.

2. Epoch length versus stimulus presentation: Utilizing pseudo-random timing introduces implementation issues beyond the DICOM standard. E.g. it may be necessary to define that if a stimulus will extend beyond the end of an epoch, it is not started, versus being cut off.

3. Presentation length: If the inherent length of a stimulus (e.g. WAV of a story, movie) is longer than the presentation time defined by a timer, it is presumably cut off. If the inherent length of the stimulus is shorter~~, should the stimulus end, or repeat?~~ , the stimulus will stop (allowing the presentation to advance to the next step, e.g. an idle stimulus).

4. Presentation scaling: The image and video representations may or may not have inherent physical scaling. Some paradigms may require particular scaling (e.g. text readability, stimulation of a particular visual field angle). This needs to be expressed somehow and then translated in the presentation system at the imaging system. Similarly for audio volume.

5. Presentation precision: temporal, spatial (image), and audio (frequency) precision are all subject to the limitations of the presentation hardware. Expectations regarding the presentation system capabilities should probably be part of the statistical model

6. Presentation method: Some paradigm schemes which can be expressed within the standard would be beyond the capabilities of current presentation software (e.g. refresh rate and resolution of displays).

7. Imaging method: Different methods of imaging for functional assessment will have different inherent limitations (e.g. temporal resolution of BOLD versus MEG) which will affect paradigm execution.

8. Oddball experiments: These could be implemented by defining a Stimulus Set per epoch, with the oddball(s) included in the set. If the set size and timing are defined to ensure the entire set will be used in an epoch, then RANDOM-NO-REPLACMENT should guarantee that the oddball will appear once at a random time in the epoch. The disadvantage of this approach is that a stimulus set must be defined for each unique epoch (trial). This could be circumvented with another layer of flexibility in the paradigm specification, e.g. a probabilistic selector between stimulus sets, but further discussion would be advisable first.

Prepared for the QIBA-fMRI DICOM Subcommittee

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A. Appendix: Real-World Examples

These examples concentrate primarily on the presentation model and stimulus object components of paradigm specification. The italicized identifiers would be DICOM instance UIDs.

1. Simple Motor Paradigm with Visual Cues

Generalized form from ASFNR "Lip Puckering" or "Unilateral Sequential Finger Tapping."

Stimulus Objects:

STIMULUS instance *s-0* TYPE Text VALUE "Please Wait"
LENGTH 0 RESPONSE (none)
STIMULUS instance *s-1* TYPE Text VALUE "Stop"
LENGTH 0 RESPONSE (none)
STIMULUS instance *s-2* TYPE Text VALUE "Go"
LENGTH 0 RESPONSE (none)

Timeline:

EPOCH instance *e-0* PHASE Standby LENGTH 0
PRESENT *s-0*
EPOCH instance *e-1* PHASE Control LENGTH 30000
PRESENT *s-1*
EPOCH instance *e-2* PHASE Stimulus LENGTH 30000
PRESENT *s-2*
EPOCH instance *e-3* PHASE Control LENGTH 30000
PRESENT s-1
EPOCH instance *e-4* PHASE Stimulus LENGTH 30000
PRESENT *s-2*
EPOCH instance *e-5* PHASE Control LENGTH 30000
PRESENT *s-1*
EPOCH instance *e-6* PHASE Stimulus LENGTH 30000
PRESENT *s-2*
EPOCH instance *e-7* PHASE Standby LENGTH 0
PRESENT *s-0*

2. Rhyming

Generalized form from ASFNR "Rhyming." Enhanced to perform randomized selection of word pairs from a collection. In the Stimulus phase, randomly ordered rhyming or not-rhyming word pairs are presented; in the control phase, the corresponding matching or non-matching bar patterns are presented. In this version, controls are matched by response (true/false) as well as pattern length. Note that the controls could be randomized separately simply by specifying a different seed than 'some-value' in the two Selector instances.

Stimulus Objects:

STIMULUS instance *s-0* TYPE Text VALUE "Please Wait"
LENGTH 0 RESPONSE (none)

STIMULUS instance *s-101* TYPE Text VALUE "BOY TOY"
LENGTH 0 RESPONSE true WINDOW 100 1000
STIMULUS instance *s-102* TYPE Text VALUE "CARE HAIR"
LENGTH 0 RESPONSE true WINDOW 100 1000
STIMULUS instance *s-103* TYPE Text VALUE "BLOW PLOW"
LENGTH 0 RESPONSE false WINDOW 100 1000
. . .
STIMULUS instance *s-201* TYPE Text VALUE "/ \ / / \ /"
LENGTH 0 RESPONSE true WINDOW 100 1000
STIMULUS instance *s-202* TYPE Text VALUE "\ / / \ \ / / \"
LENGTH 0 RESPONSE true WINDOW 100 1000
STIMULUS instance *s-203* TYPE Text VALUE "/ / \ \ / \ \ /"
LENGTH 0 RESPONSE false WINDOW 100 1000

. . .

STIMULUS-SET instance *set-1* OF *s-101, s-102, s-103* … END *set-1*

STIMULUS-SET instance *set-2* OF *s-201, s-202, s-203* … END *set-2*

Selectors:

SELECTOR instance *seq-1* RANDOM-NO-REPLACEMENT
SEED some-value STIMULUS-SET *set-1*

SELECTOR instance *seq-2* RANDOM-NO-REPLACEMENT
SEED some-value STIMULUS-SET *set-2*

Timeline:

EPOCH instance	*e-0*	PHASE Standby	LENGTH 0
PRESENT	*s-0*		
EPOCH instance	*e-1*	PHASE Control	
PRESENT	*seq-2*	REPEAT	LENGTH 3000
EPOCH instance	*e-2*	PHASE Stimulus	LENGTH 30000
PRESENT	*seq-1*	REPEAT	LENGTH 3000
EPOCH instance	*e-3*	PHASE Control	LENGTH 30000
PRESENT	*seq-2*	REPEAT	LENGTH 3000
EPOCH instance	*e-4*	PHASE Stimulus	LENGTH 30000
PRESENT	*seq-1*	REPEAT	LENGTH 3000
EPOCH instance	*e-5*	PHASE Control	LENGTH 30000
PRESENT	*seq-2*	REPEAT	LENGTH 3000
EPOCH instance	*e-6*	PHASE Stimulus	LENGTH 30000
PRESENT	*seq-1*	REPEAT	LENGTH 3000
EPOCH instance	*e-7*	PHASE Standby	LENGTH 0
PRESENT	*s-0*		

Notes:

1) The paradigm incorporates two sequences in order to have stimulus and control selections match (by using the same seed, the pseudo-random generator produces the same sequence).
2) Each phase should perform ten stimulus presentations.
3) The response window is quite tight (1 sec after presentation) but obviously could be relaxed.
4) The use of a sequence in a stimulus presentation is accompanied by a control tag specifying how the sequence is being used: START: the sequence is (re)started from the first UID; NEXT: the next UID in the sequence will be used; REPEAT: the next UID(s) in the sequence will be used until the end of the EPOCH (implicit START if the first use of the sequence).

3. Further examples

Need: randomized timing examples; event-related paradigm design examples.