# Incorporation of Imaging-Based Functional Assessment Procedures into the DICOM Standard
# Draft version 0.6 –10/13/2011

## 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.

The structure of this document is: a background section outlining the purpose of the proposal; a framework from the functional assessment workflow; and a data dictionary to ultimately represent the objects defined to implement the workflow. This is supplemented by appendices containing real-world examples of functional assessment as captured in the proposed framework; and further background and justification of the framework.

## II. Background

Functional MRI (fMRI) is arguably the most widely-used functional assessment imaging method, and has achieved the status of a reimbursable radiology technique.[1] As previously described [2], 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 activation (‘resting state’).

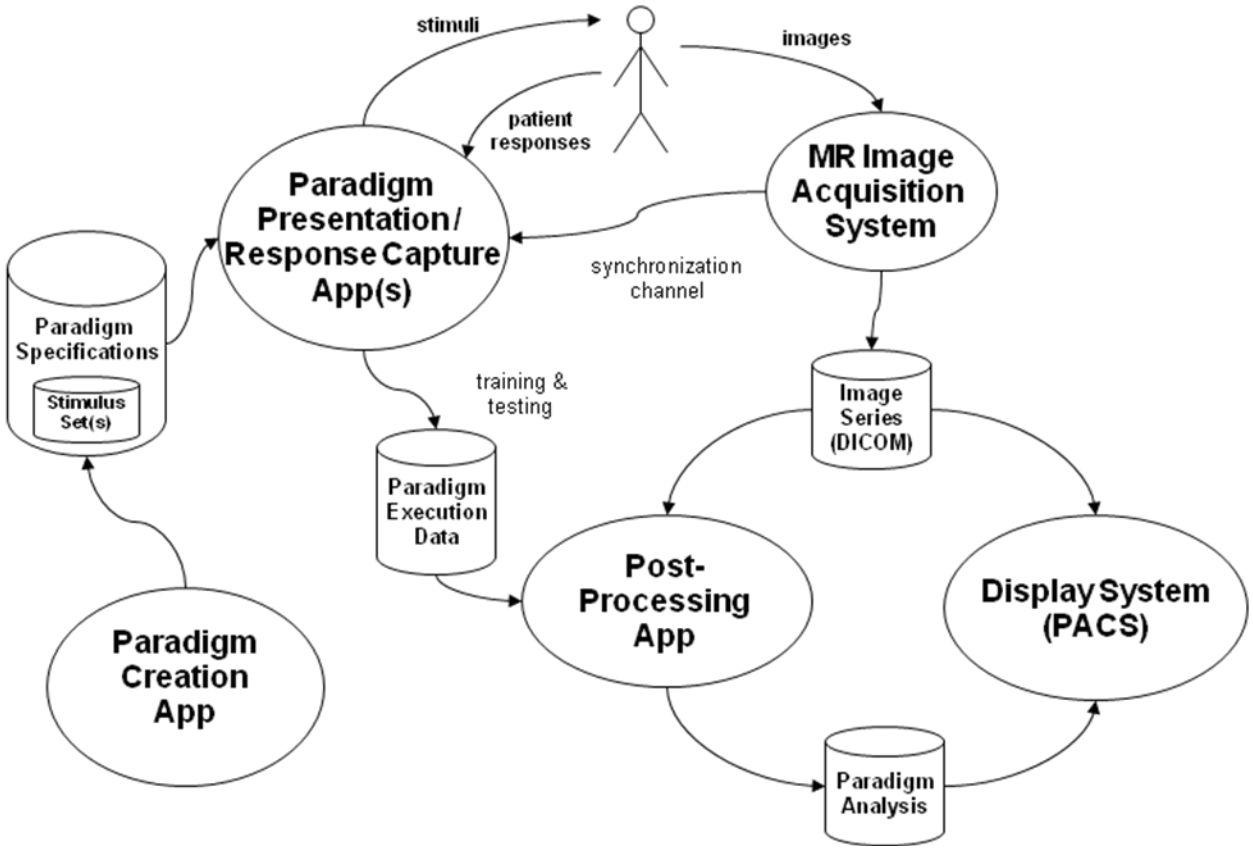
2. Although fMRI based on blood oxygen level dependence (BOLD) is the focus of the QIBA-fMRI committee, assessment of cortical activation may be performed with other imaging sequences and modalities (e.g., MEG). Therefore, in striving to define the most generally useful DICOM extensions, we will strive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

[1] ASFNR / CPT Codes, http://www.asfnr.org/cpt_codes.html
[2] http://qibawiki.rsna.org/images/7/7a/DrTuckerSlides_2010_11_WG16.ppt_-Compatibility_M.pdf

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, reimbursement documentation.

Figure 1 (below) is a high level workflow of the important applications and data elements required for fMRI planning, acquisition, and processing.[3]



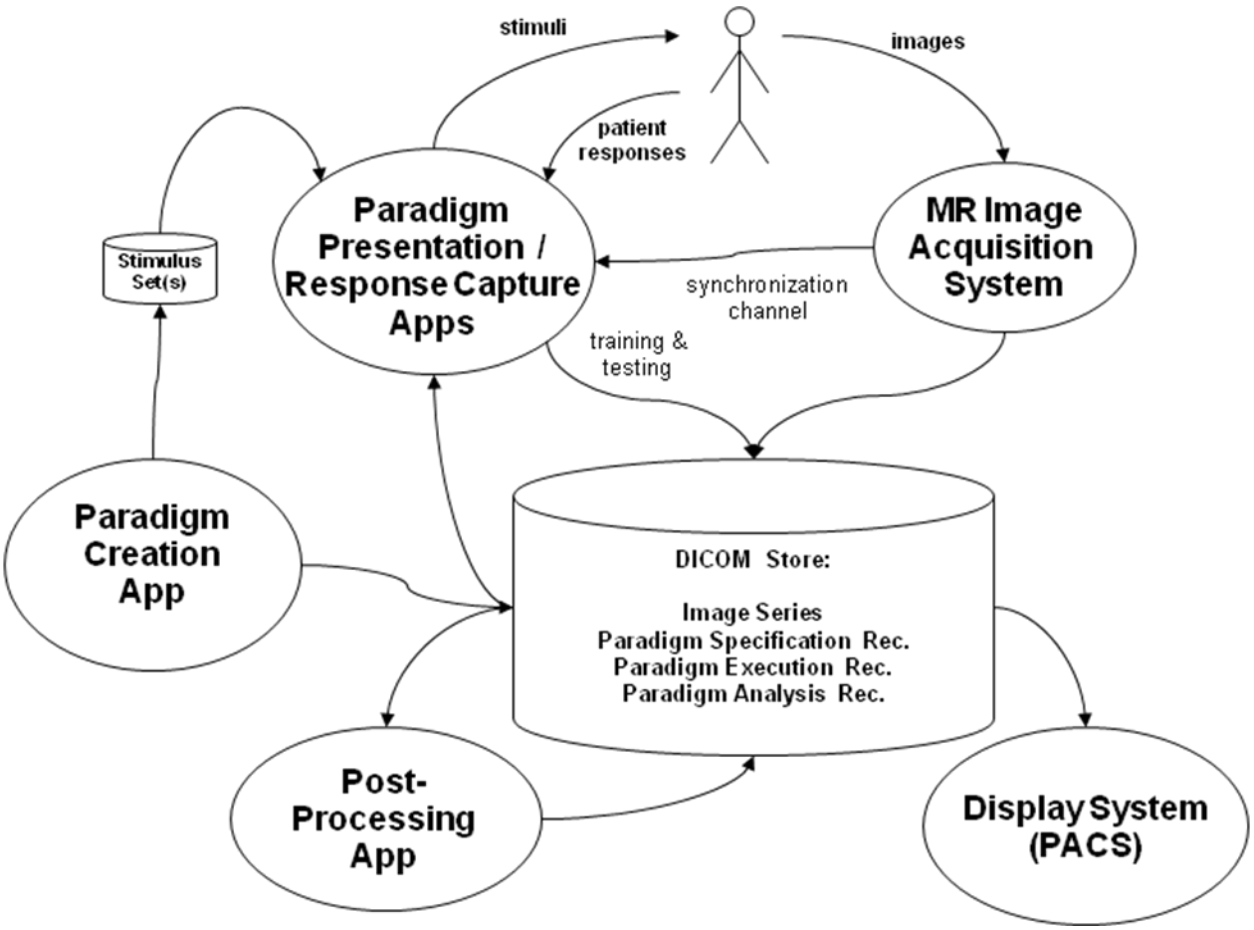

The figure depicts up to six unique applications with at least four data stores that must be considered in order to successfully acquire and process a single fMRI series. (Patient training and testing might occur with the same application or different, in or away from a scanner.) While a scanner vendor may provide customers an integrated solution that addresses all applications and data elements, this is not the general case. The fact that

[3] Courtesy of Brian Lenoski, Doug Tucker et al (Medical Numerics, Inc.); included and adapted with permission.

multiple vendors may supply parts of the solution drives the need for fMRI standardization. These various companies all have proprietary mechanisms for representing the various data elements; thus, interoperability is difficult if not possible, innovation is inhibited, and the utility and availability of fMRI is diminished. The applications and systems are described below.

| System | Responsibilities |
|---|---|
| Paradigm Creation application | 1. Specify when and how paradigm events should occur (e.g., the paradigm stimulus and statistical timings).<br>2. Specify the actual stimulus objects (text, pictures, audio, video).<br>3. Generate Paradigm Specification record. |
| Stimulus Presentation application | 1. Execute the paradigm, i.e., paradigm playback.<br>2. Synchronize with MR Image Acquisition.<br>3. Receive and record patient responses.<br>4. Generate Paradigm Execution record |
| Response Capture application | 1. Capture patient responses.<br>2. Generate Patient Response data of Execution record |
| MR Image Acquisition | 1. Acquire the image data.<br>2. Synchronize with Stimulus Presentation application<br>3. Generate DICOM image Series |
| Post-Processing application | 1. Process the fMRI series (including pre-processing, statistical analysis, etc…) from Paradigm Execution rec.<br>2. Generate fMRI result images.<br>3. Generate Paradigm Analysis record |
| Display System | 1. Display the results of the fMRI analysis (may be a PACS or dedicated workstation) |

A DICOM approach to this workflow might look more like Figure 2, below:




All of the data items (except, perhaps, stimulus sets – sound files, image files, etc.) are objects in DICOM records, as discussed in the next section. The records could be sent directly from application to application, although use of a DICOM store offers more flexibility (e.g., applications could be run on demand to 'pull' data). A DICOM implementation should promote interoperability of the requisite applications, as well as simplifying common healthcare IT issues such as communications, security, and archival storage.

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. Note that each record incorporates, directly or by reference, the information of the preceding records.

It is proposed that these be three new top-level DICOM records, produced by paradigm creation, stimulus presentation / patient response, and post-processing applications, respectively. These applications run on one or more workstations, utilizing DICOM communications to share these records, either directly or through a DICOM store.

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. Since the analysis generally depends upon the characteristics of the stimuli (stimulus versus control, etc.) as opposed to the stimuli themselves, using DICOM to represent the stimuli per se is probably a low priority.

See Appendix B for rationale and expanded discussion.

1. Paradigm Specification

a. Identification (beyond UID of object itself)
    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. 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
vi. Response Latency

r. Reference Series UID of imaging data collected during assessment.

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
ii. BOLD effect – neurovascular uncoupling (NVU)
Perfusion mapping, cardiovascular reactivity, etc,
f. Motion correction
i. Algorithm
ii. Results
E.g. statistics; time course of deviation removed in multiple translations & rotations
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

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

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

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

j. Processed results: Contrast-Noise map

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

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
   vi. Response Latency

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 (Paradigm Execution record and concurrent imaging), 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 description of 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 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 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: seed, Stimulus-set
    RANDOM-NO-REPLACEMENT: seed, Stimulus-set
    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. Phase: The state of patient action during a functional assessment procedure. Block paradigm designs typically have stimulus versus control phases, with the control intended to cancel out irrelevant cortical activation leaving the desired activation elicited by the stimulus phase. A variation on this uses left / right phases to elicit two desired activations, represented alternately in the results. Temporal phase mapping similarly eschews the control phase, sequentially eliciting a series of functional activations.

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. 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.

13. 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.

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

15. Epoch Event: Start of an epoch, logged in the Execution of the paradigm, indicating the paradigm phase.

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

17. 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.

18. 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 Priorities

DICOM may be used to standardize the data elements involved with functional assessment (fMRI) planning, acquisition, and processing.[4] Following is a list of the goals with respect to standardization of each identified data element:

[4] Table courtesy of Brian Lenoski, Doug Tucker et al (Medical Numerics, Inc.); included and adapted with permission.

| Data Element | Standardization Goals |
|---|---|
| Stimulus Sets | 1. Uniquely identify individual stimulus objects.<br>2. Standard protocol for finding and loading the set of stimulus objects needed to play a paradigm? |
| Paradigm Specification | 1. Enough information such that a Paradigm Specification created by the Paradigm Creation application from Company A can be played by the Stimulus Presentation application from Company B. |
| DICOM Series | 1. Enough information such that an fMRI DICOM Series from Company A's MR Image Acquisition System (along with the correct Paradigm Execution data element from Company B) can be processed by Company C's Post-Processing application. |
| Paradigm Execution<br><br>(includes Patient Responses) | 1. Enough information such that a Paradigm Execution record (including patient responses) from Company A (along with the fMRI DICOM Series from Company B's MR Image Acquisition System) can be processed by Company C's Post-Processing application. |
| Synchronization Channel | 1. Enough information such that an fMRI DICOM Series from Company A's MR Image Acquisition System can be associated with the correct Paradigm Execution data element created by Company B's Stimulus Presentation application. |
| Paradigm Analysis | 1. Enough information such that the Paradigm Analysis record created by Company A can be used by Company B's Display System.<br>2. The necessary and sufficient information such that a physician can make appropriate clinical use (screening, diagnosis, treatment planning, etc.). |

This section will identify three levels of implementation priority: Immediate, Basic, and Extended. Many manufacturers may feel they have adequately supported functional assessment with private DICOM tags or non-DICOM information. Realistically, achieving any industry acceptance for a full DICOM implementation of functional assessment support is unlikely. By prioritizing, we would have to achieve consensus on at least fundamental workflow items that would provide the most benefit for the invested time.

1. Immediate: These would remove current uncertainty from image processing associated with functional assessment, and enhance integration of functional assessment results into the clinical radiology workflow.

    a. Temporal Synchronization: Most systems used for fMRI employ a hardware sync pulse from the scanner to coordinate paradigm presentation by an external system with image acquisition. As long as all paradigm execution timing (epochs, stimuli, and patient responses) is performed by one external application and/or hardware platform, hardware-synchronized to the scanner, the timing needed for analysis can be relative to the paradigm execution record. If multiple applications require coordination, a more sophisticated

system (e.g. DICOM Synchronization Frame of Reference[5]) could be adapted.

Q: What is the degree of adoption of DICOM Sync FoR among MR scanner vendors?

b. Some currently available DICOM data types would enhance current imaging for functional assessment. Examples: use of Enhanced MR multi-frame[6] for EPI series would dramatically reduce the number of instances, decreasing overhead in the DICOM infrastructure.

Q: What is the degree of adoption of DICOM Enhanced MR multi-frame mode for EPI series among MR scanner vendors?

c. Some new DICOM objects should be provided in imaging headers for functional assessment scans. Examples: Explicit tags identifying discarded pre- and post-acquisitions (also known as 'dummy samples').

d. Analysis of paradigm execution results in functional activation maps usually quantified by a statistical parameter (r, t, F, p) and displayed using a color palette. The maps must remain quantifiable, i.e., not reduced to a DICOM Secondary Capture level of color-only information, when presented for clinical use. Another feature of Enhanced MR (above), DICOM Real-World Value Mapping, could be used to document the meaning of the stored values. (This includes use of Slope / Intercept tags to express the relationship.)

Q: What is the degree of adoption of Enhanced MR's Real World values among PACS viewer vendors?

e. Practices vary regarding colorization of functional activation maps, dictating the need for flexibility in clinical application. Storage of maps as fixed DICOM screen capture (SC) type RGB images results in loss of quantification capability.

Enhanced MR contains color look-up table (LUT) capability, which would permit definition of a default color mapping without loss of quantitative information, and permitting change of mapping (different LUT) during clinical use. A further extension, Color Image Storage,[7] may also help with functional imaging by providing a way to convey color palettes with the imaging.

[5] DICOM Suppl. 30: Waveform Interchange, at http://medical.nema.org/Dicom/supps/sup30_lb.pdf
[6] DICOM Suppl 49: Enhanced MR Image Storage SOP Class, ftp://medical.nema.org/medical/dicom/final/sup49_ft.pdf
[7] DICOM Suppl. 141: Enhanced MR Color Image Storage SOP Class, at ftp://medical.nema.org/medical/dicom/final/sup141_ft2.pdf

Q: What is the degree of adoption of Enhanced MR color LUT and Color Images among PACS viewer vendors?

2. Basic: Additional DICOM objects forming a Paradigm Execution record, documenting key information about the paradigm performed necessary for clinical interpretation. This would include DICOM objects for: basic paradigm identification; personnel identification; and paradigm execution results. These would be created by the stimulus presentation application. (This may not be sufficient to completely describe processing in detail (e.g. statistical model) but should suffice for generic direction of processing (timing, phases, expected responses).

    a. DICOM Study UID synchronization is needed to provide common identification for paradigm execution results not created by the scanner performing the imaging. In a basic implementation the scanner can originate the Study UID which is passed along to other application (paradigm presentation).

    b. If paradigm execution information can originate in a patient encounter *before* imaging (e.g. training session) then either i) training data is held until testing (imaging) takes place, or ii) some patient scheduling facility links the training with later testing sessions. DICOM Referenced Study[8] may be useful.

    c. A new record capturing paradigm execution can be defined. This will require new tags for basic paradigm identification; design definition (e.g. phases used) and paradigm execution (phase, stimulus, and response events, as well as basic behavioral and imaging assessments).

    d. Currently available tags for human performer, date/time stamps, etc. can be applied in capturing the training and testing workflow.

3. Extended: Full description of paradigms in DICOM format, including statistical models and specific characterization of stimuli; full analysis records in DICOM format.

    a. Paradigm Specification record documenting paradigm design.

    b. Paradigm Analysis record organizing activation map(s) with other results including activation time-series. Enhanced MR may help organize multiple activation maps (e.g. different significance levels, clustering strategies, smoothing) into multi-frame images.

[8] DICOM Suppl. 23: Structured Reporting Storage SOP Classes, at http://medical.nema.org/Dicom/supps/sup23_lb.pdf

c. DICOM Waveform storage may be of value in representing activation, motion, etc. time series results.

*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.

## B. Appendix: Guidance & Rationale

This section captures the rationale for the proposed directions as well as alternative viewpoints expressed during the formulation of the proposal. It follows the organization of the framework in Section III. (Discussion items previously found in Section V have been integrated here.)

1. *Paradigm Specification*

Although the framework proposes to use DICOM for the entire specification, the implementation could be reduced to key elements required for analysis.

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.

*a. Identification*

Paradigms are far from standardized (although some attempts have been made[9]), and should be identified by source and version.

*b. Imaging Model*

Paradigm specifications exist independently of the scanners, but depend critically upon the proper setting of scan parameters. This dictates the need for at least some scan parameter specifications to reside in the paradigm specification for purposes of validation.

Otherwise, it should be possible to express paradigm characteristics in physical terms independent of scan parameters.[10]

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.

*c. Statistical Model*[11]

Why is a statistical model needed? To answer this we must look at what is needed to analyze the data.

At a minimum we need to identify the statistical conditions of interest which means:

1. block design:
    - start and end time of each block (epoch) and the block's condition

[9] ASFNR / fMRI BOLD Paradigms, http://www.asfnr.org/paradigms.html
[10] Brian Lenoski, Doug Tucker (Medical Numerics, Inc.)
[11] Paraphrased from remarks of Brian Lenoski, Mike Fonte (Medical Numerics, Inc.)

2. event related:
    - start time and duration of each event and its condition
3. hybrid designs:
    - a combination of the above

For the proposed paradigm specification one could look at (extract) the epoch type of each stimulus event and when they occur to derive the above information but that is inefficient and can lead to confusing things such as, "how do you label a 'primer' stimulus event?" It also does not allow for defining 'external conditions' (such as conditions of no interest, see below) or more advanced/complicated models where statistical conditions are not tightly coupled with stimulus events.

In order to analyze the results of a functional imaging assessment, we propose addition of the following concepts:

1. Statistical Condition: a statistical condition models some aspect of the observed response. Specifically, a statistical condition can have one of the following types
    a. Experimental Condition
    b. External Condition
    c. Parameterized Condition
    d. Others?
2. An Experimental Condition will typically model the presentation of stimuli expected to invoke a hemodynamic response, i.e., these are the conditions that are convolved with the HRF model in order to produce the expected/ideal response. Each experimental condition is composed of a name/category (e.g. Right Hand, A, etc…) and an ordered sequence of Statistical Events. (Thus, experimental conditions are analogous to an epoch; they are more general in that they exist independent of the stimulus presentation model. This allows more complex experiments, e.g., oddball, to be modeled by the paradigm specification).
3. A Statistical Event is simply a tuple of 3 values (onset, duration, weight). An ordered sequence of statistical events describes the timing of an experimental condition. Furthermore, almost all existing fMRI SW packages (SPM, AFNI, FSL) have a mechanism for specifying an experimental condition using a sequence of onset, duration, and weight tuples.
4. External Conditions are sequences of numerical values that typically model some physiological aspect of the observed signal (BOLD or

otherwise). For example, including the estimated motion parameters in a GLM fMRI analysis is one use of external conditions. External conditions are the most general statistical conditions in that (almost) no processing is required to use them. Typically, an external condition will have as many values as there are volumes/samples in the functional imaging acquisition.

5. Parameterized Conditions are typically used to model structured noise in the observed fMRI signal. For example, including a column of all "1's" in a GLM analysis is meant to model the non-zero signal average. Sinusoidal parameterized conditions are often used to model noise in fMRI analyses.

Functional assessment (fMRI) Contrast Descriptions: a mechanism for encoding phase contrast descriptions is needed. For example, a paradigm with A/B/X phases might generate any, all, or some of the following contrast images: A vs X, B vs X, A+B vs X, … and so on. This information should be encoded both up front with the Paradigm Specification (allows for real time and automated analysis) and at the end of processing in the Paradigm Analysis. We propose the following fields to describe an fMRI contrast:

1. Contrast name
2. Contrast Type (t, F, Z, …)
3. Contrast Weights (one for each statistical condition in the paradigm specification)

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.

*d. Stimulus Set(s), each a set of Stimulus Objects, as follows:*

(To be supplied)

*e. Presentation model*

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.

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, the stimulus will stop (allowing the presentation to advance to the next step, e.g. an idle stimulus).

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.

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).

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.

2. *Paradigm Execution*

There needs to be some mechanism to synchronize [i.e. identify as belonging with] data in the 'Paradigm Execution Data' and the image data acquired by the MR scanner. This is particularly important if the Paradigm Execution Data exists independently of the image data. The Paradigm Execution Data should include the DICOM UID identifying the corresponding MR image DICOM series (or equivalent). With this, the processing system could 'do the right thing' when it receives a new Paradigm Execution Data object.

Getting the DICOM UID from the MR scanner to the paradigm presentation system (for inclusion in the Paradigm Execution Data object) is probably beyond the scope of the document.[12]

Temporal Synchronization between DICOM objects that are produced by different systems must be addressed and can be done a number of ways. In DICOM there is a Synchronization module (see C.7.4.2) and there is UID for the international UTC time standard usually implemented by the use of NTP. A shared trigger event could also be used. Both the image object and the execution object would need to contain the same Synchronization Frame of Reference UID (0020,0200). …if most scanners are triggering the paradigm presentation system, then this would be good to know as this could ease how we approach the synchronization process. It would be good to get QIBA consensus on whether this

[12] Paraphrased from remarks of Doug Tucker (Medical Numerics, Inc.)

could be standardized. I see that this is the only way we could have paradigm information in the images themselves (stimulus on/off for example).[13]

(Author comment) If we assign responsibility for time base to the Stimulus Presentation application, which is in turn synchronized by the scanner, then time synchronization between imaging data and the paradigm execution record is accomplished through the synch event. (The stimulus application might be executed by the scanner itself, some tightly coupled sub-system, or an independent 'Stimulus PC.') Timebase resolution and accuracy is dependent upon both scanner sync characteristics and the performance of the stimulus presentation platform. These should be defined in manufacturer specifications and are beyond the scope of the DICOM standard.

In this document the Stimulus Presentation and Patient Response applications are assumed to either be one and the same, or running simultaneously on the same platform, so that they share the same time base.

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*

[13] Remarks of Bob Haworth (GE Healthcare, DICOM WG-16)

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*

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*

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

*f. Motion correction*

*i. Algorithm*

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

*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*

*iii. Analytical model, e.g. GLM, ICA and associated setup*

*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*

*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*

*j. Processed results: Contrast-Noise map*

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

*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*
vi. *Response Latency*

m. *Processed results: Other analyses*
i. *Laterality*