Supplement 2

SPP Radiomics – Consensus Radiomics Workflow Definition

A SPP Radiomics Workflow Definition Supplement

Version: 1.0 – 2024/03/15

Scope: This is a supplement for the publication “Radiomics Workflow Definitions and Challenges of Implementation in Clinics: a Delphi-based Interdisciplinary Consensus” by the Scientific Priority Program Radiomics (DFG SPP2177) by the Germany Research Foundation. The supplement contains the consensus definition after the delphi process described in the publication. It also reflects all accepted additions and refinements proposed by the expert panel as well as the aspects that remain controversial. In addition it provides a mapping table between the consensus definition and analyzed literature.

Legend

Consensus color encoding:

Consensus: >75% agreement (Agree or Strongly Agree)	
Minor controversy >55% / <75% agreement (Agree or Strongly Agree)	
Major controversy <55% agreement (Agree or Strongly Agree)	

Phases: ***Are printed italic and bold.***

Aspects: Are printed in normal text.

Terminology

- Workflow: A workflow is structured in phases and their aspects and comprises any activity/step, to plan, to conduct and to report the building of an image feature-based prediction model.
- Phase: Phases represent different fundamental workflow steps and therefore can be found to a certain extent in every Radiomics workflow. A phase may contain one or more aspects. Between phases there is a logical dependency and therefore the order is not arbitrary.
- Aspects: Aspects are activities that take place within a phase. Aspects are often optional and they have per se no fixed order (sorting in this document is alphabetically by the English name of the aspect). As an effect of this ambiguity, the literature partially strongly differs on the aspects and their sequence. In some cases aspects are arranged in hierarchies (e.g. because we found sub aspects in the literature).

Remarks

- Mandatory/optional workflow elements: As a default, aspects of a workflow can be regarded as optional (in occurrence, order or number). The list below compiles aspects that are documented in literature and are commonly found in Radiomics workflows. Nevertheless, we think that some aspects are crucial in the Radiomics workflow to ensure the validity and reliability of its results. Those “mandatory” aspects are indicated in the column “Mandatory”. Workflow phases that have at least one mandatory aspect are also mandatory.
- Machine learning / Deep learning: Deep learning techniques are increasingly applied also in the context of Radiomics workflows. They are (potentially) applicable at many aspects of the workflow; from simply replacing single aspects (like doing the annotation) up to replacing large parts of the workflow (e.g. end-to-end approaches). Therefore, the usage of deep learning techniques in the context of the workflow definition is not represented by additional optional aspects (which would be highly redundant) but by indicating which aspects can be replaced/covered by a deep learning technique (indicated by the column “ML”).

Workflow Definition

English Name	German Name	Definition (English)	Mandatory	ML
Study design	***Studiendesign***	***Definition of the (clinical) research question, the imaging data and other data required as well as the analysis strategy. The definition should precede the analysis and always serves to ensure a reproducible and representative analysis.***	X	
Choice of imaging data	Definition der Bildgebungsdaten	Definition of image data / standardization of the imaging protocol to ensure the feasibility and reproducibility of the analysis.	X	
Choice of prediction target	Definition des Prädiktionsziels	Definition of the prediction goal of the model. (e.g. stratification with respect to progression-free survival).	X	
Choice of region of interest	Definition der Zielstruktur	Definition of the structures (ROI) to be analyzed incl. the segmentation protocol.	X	
Definition of further data (non-imaging)	Definition weiterer Daten (keine Bildgebungsdaten)	Specification of the non-imaging data used for modeling. The data can be both modeling features and data on relevant endpoints. Due to the often low standardization of many non-imaging data, the formats and terminologies used should also be defined in advance and the widest possible/established options for coding should be used.		
Definition of the analysis and modeling strategy	Definition der Analysestrategie	Definition of the analysis and modeling strategy to answer the defined research question with the selected data.		
Definition of the clinical added value or the expected benefit	Definitionen des klinischen Mehrwertes (Motivation) und des erwarteten Nutzens	Definition of the added clinical value or the expected benefit, which should be achieved by the created model.		
Data acquisition	***Datenakquisition***	***Summary of all activities necessary for prospective image data collection/standardization including associated metadata.***		
Image acquisition	Bildaufnahme	This aspect refers solely to the image acquisition and the associated acquisition parameters.		
Phantom studies	Phantomstudien	Use of phantom studies to calibrate imaging systems for a prospective study; especially for multi-center studies. Furthermore, phantom studies can be used to investigate differences between scanners and segmentation methods (inter-observer variability).		
Reconstruction	Rekonstruktion	Use of a reconstruction algorithm to reconstruct the image volume from the raw data.		X
Test-retest imaging	Test-Retest-Bildgebung	Experimental reproducibility assessment by repeating recordings with temporal delay to detect normal variations in the image signal (test retest).		

Data management	***Datenmanagement***	***This phase contains all the actions necessary to compile the study data for the analysis and make it available for processing in the radiomics pipeline.***	**X**	
Data archiving	Datenarchivierung	Archiving / Storage of data for potential re-analysis, subsequent validation or further research. FAIR principles should be regarded/supported by the chosen archiving strategy.		
Data format conversion	Datenformat-Konvertierung	Conversion of the data into other data formats (e.g. from DICOM to NIFTI). This is solely the transformation of the format (in the case of a lossless conversion). The conversion of the actual data takes place in the "Data conversion" aspect in the "Image processing and segmentation" phase.		
Data transfer and import	Datentransfer und -import	Transfer and import of the data into a target system which is required for the execution of the workflow (e.g. the evaluation is not conducted in the same facility or is conducted in a non-integrated system).		
Ethics and data protection	Ethik und Datenschutz	Display of ethical vote, detailing on data protection means (anonymisation/ pseudonymisation) also for secondary use of the employed data.	**X**	
Export of Imaging Data	Export der Bilddaten	Export of Imaging Data (e.g. DICOM images) from the data archive (e.g. PACS) to be able to use them in the Radiomics pipeline.	**X**	
Multi disciplinary data curation and integration	Multidisziplinäre Datenkuratierung und -Integration	Optional inclusion of non image data (e.g. clinical data, genetic data) that should be used for the modeling.		
Record linkage (of multi disciplinary data)	Verknüpfung der Datensätze (multidisziplinär)	Linking/merging of data (from different primary sources; e.g. multidisciplinary data with different IDs) of a subject.		
Image processing and segmentation	***Bildverarbeitung und Segmentierung***	***This phase contains all actions necessary to create the segmentations and prepare images as well as segmentations for feature calculation.***		**X**
Data conversion	Datenkonvertierung	Conversion of the image signal (image data) into another representation (e.g. conversion of PET signal image into Standardized Uptake Values (SUV)).		**X**
Image filtering	Bildfilterung	Processing of the image signal with filters (e.g. noise reduction, gray value normalization,...).		**X**

Image geometry harmonization and resampling	Harmonisierung der Bildgeometrie und Resampling	Step to convert all images in the evaluation into an identical image geometry, in order to make voxel size-dependent features comparable. The harmonization can be done before the segmentation (the segmentation is thus performed on the harmonized geometries) or after the segmentation (The segmentation must therefore also be harmonized and resegmentation may be necessary).		**X**
Image registration	Bildregistrierung	Transfer of images to target geometries with a given mapping rule (e.g. to compensate for motion artifacts, to spatially align multimodal images or to normalize to a reference anatomy).		**X**
Quality control of segmentation	Qualitätskontrolle der Segmentierung	Checking and correction of segmentation (especially at its edges) to correct errors that were e.g. introduced by the segmentation or by "harmonization of image geometry" (post segmentation).		**X**
Segmentation/annotation	Segmentierung/Annotation	Segmentation/annotation of the defined region of interest based on the defined protocol.		**X**
Image quality assessment	Qualitätsbewertung der Bilddaten	The analysis of outliers is used to evaluate the quality of the used image material. For the assessment general criteria (e.g. correct modality or right body part) as well as study specific criteria (e.g. need minimal resolution, absence of artifacts) can be used. The assessment can be implemented by expert decision as well as automated quality control (to support scalability and reproducibility, it is adviseable to implement a process that is as quantitative and automated as possible.	**X**	**X**
Feature extraction	***Merkmalsextraktion***	***In this phase, all aspects are summarized that are necessary/relevant for feature extraction, i.e. the derivation of quantitative information from the segmented images using mathematical formulas.***	**X**	**X**
Feature calculation	Merkmalsberechnung	The actual process of calculating individual features based on the input data, the formula/algorithm and their parameterization.	**X**	**X**
Intensity discretization	Intensitätsdiskretisierung	A discretization/binning of intensities within the ROI is performed to make the calculation of texture features comprehensible and to suppress noise. Binning can be performed for all features or adapted for specific features.		**X**

Preprocessing	Vorverarbeitung	The preprocessing steps in this phase are used to prepare the images before feature extraction. In contrast to the aspect "Image Processing" (Phase Image Processing & Segmentation), "Preprocessing" only includes preprocessing steps that are needed for specific features (e.g. a Fourier transformation) but have no general relevance or validity. In the works studied, the preprocessing steps named were i.a. filtering in general, edge reduction or smoothing.		**X**
Quality control of calculated features	Qualitätskontrolle der berechneten Merkmale	Quality control (e.g. through automatic plausibility check or random checks) of the calculated features.		**X**
ROI extraction	ROI-Extraktion	Isolation of one or more of the ROIs from the rest of the image (e.g. by replacing excluded pixels/voxels with NaN). This step depends on the feature and the implementation of the extraction method.		**X**
Modeling	***Modellierung***	***This phase contains all aspects that are necessary to establish a model that, based on given input data (radiomic features, clinical features, etc.), allows prediction in terms of the defined prediction goal.***	**x**	
Adaption of the analysis and modeling strategy	Anpassung der Analyse- und Modellierungsstrategie	Sometimes it can be necessary to adapt the analysis strategy of the study in order to achieve the research goal with the given study data. This aspect covers this necessity, but should be avoided if possible. If one has to adapt the strategy and diverge from the original study design, it should be handled very carefully and statistically double-checked to ensure the validity and integrity of the results. As later changes can introduce bias, over fitting or statistical errors and alike, the results could otherwise be compromised.	**X**	
Dimensionality Reduction	Dimensionsreduktion	Combination of several features into a new feature (e.g. by Principal Component Analysis).		
Exploratory analysis	Explorative Analyse	Interactive analysis on the predictive power of different combinations of radiomic features and non-radiomic features. This can be used to perform more targeted feature selection and reduction. It is important that this aspect is not done with the data for testing.		
Feature harmonization	Merkmalsharmonisierung	Mathematical method to correct batch effects (e.g. location-dependent variations during the image acquisition). In contrast to a harmonization of the gray values (e.g. also by phantom studies, see above), here the harmonization takes place only after the extraction of the features.		

Feature selection	Auswahl von radiomischen Merkmalen	Selection of radiomic features that are relevant and informative for the planned task, from the extracted radiomic features (e.g. mRMR). Another criterion is the exclusion of non-reproducible radiomic features.		
Model building	Modellentwicklung	The optimization of a model, to ensure a best possible prediction of the prediction targets based on the selected features. This includes i.a. the parameter optimization of parameterized models (Training) or architectural model/ hyperparameter optimization (Validation).	**X**	
Testing	Testen	Testing using dedicated data, which is not used for model training, serves the final evaluation of the suitability of the radiomics model (e.g. with regard to robustness/generalizability, predictive quality/accuracy...). Ideally, this is done by means of an independent test set. The testing can also be done by means of cross-validation (whereby it must then be ensured that all aspects mentioned above must be cross-validated, including e.g. nested cross-validation for hyperparameter optimization). Remark: The term “Testing” was preferred over often found “Validation” because validation in ML normally means the optimization of the architectural model/hyperparameter and “Testing” is semantically fitting term in ML.	**X**	
Reporting	***Report***	***Report of the results including all necessary metadata (data provenance, data source, processing steps, data quality) as part of publications or the enablement of subsequent usage . The FAIR principles should be regarded/implemented in the report.***	**X**	
Open source publication of methods and tools	Open source Publikation der Methoden und Werkzeuge	Publication (e.g. via public code repositories) of the used program source codes and analysis scripts to support reproducibility of the study setup and reuse of the published methodology. ***The FAIR principles should be regarded/implemented in the code publication.***		