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| **Abstract:** | Radiology has been essential to accurately diagnosing diseases and assessing responses to treatment. The challenge however lies in the shortage of radiologists globally. As a response to this, a number of Artificial Intelligence solutions are being developed. The challenge Artificial Intelligence radiological solutions however face is the lack of a benchmarking and evaluation standard, and the difficulties of collecting diverse data to truly assess the ability of such systems to generalise and properly handle edge cases. We are proposing a radiograph-agnostic platform and framework that would allow any Artificial Intelligence radiological solution to be assessed on its ability to generalise across diverse geographical location, gender and age groups. |

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**TABLE OF CONTENTS**

| Page |
| --- |
| [1 Introduction 4](#_Toc52722764)  [1.1 Document Structure 4](#_Toc52722765)  [1.2 Topic Description 4](#_Toc52722766)  [1.2.1 Impact of Benchmarking 5](#_Toc52722767)  [1.3 Ethical Considerations 6](#_Toc52722768)  [1.4 Existing AI Solutions 6](#_Toc52722769)  [1.4.1 Use Case Descriptors 6](#_Toc52722770)  [1.4.2 Collected AI solutions and use cases 6](#_Toc52722771)  [1.5 Imaging Modalities 8](#_Toc52722772)  [1.6 Existing work on benchmarking 15](#_Toc52722773)  [2 AI4H Topic group 15](#_Toc52722774)  [3 Method 16](#_Toc52722775)  [3.1 AI Input Data Structure 16](#_Toc52722776)  [3.1.1 Image Conversion Considerations 16](#_Toc52722777)  [3.2 AI Output Data Structure 17](#_Toc52722778)  [3.3 Test Data Labels 17](#_Toc52722779)  [3.4 Scores & Metrics 17](#_Toc52722780)  [3.5 Undisclosed Test Data Set Collection 21](#_Toc52722781)  [3.6 Benchmarking Methodology and Architecture 21](#_Toc52722782)  [3.6.1 Benchmarking Solution 22](#_Toc52722783)  [3.6.2 Evaluation Metrics 23](#_Toc52722784)  [3.6.3 Benchmark Categorizations 24](#_Toc52722785)  [3.6.4 Evaluation Data 25](#_Toc52722786)  [3.6.5 The Panel of Expert Radiologists 25](#_Toc52722787)  [3.6.6 Test Radiologists 26](#_Toc52722788)  [3.7 Evaluation Data Availability 26](#_Toc52722789)  [3.8 Feasibility 26](#_Toc52722790)  [3.9 Privacy and Security 26](#_Toc52722791)  [3.10 Impact 27](#_Toc52722792)  [3.11 Reporting Methodology 27](#_Toc52722793)  [4 Results 27](#_Toc52722794)  [5 Discussion 27](#_Toc52722795)  [6 Declaration of Conflict of Interest 28](#_Toc52722796) |

**List of Tables**

| Page |
| --- |
| [Table 1: Imaging Modalities 9](#_Toc52722797)  [Table 2: Image Conversion Considerations 16](#_Toc52722798) |

**List of Figures**

| Page |
| --- |

[Figure 1: A prototype of the radiograph-agnostic precision evaluation platform. 22](#_Toc52722799)

[Figure 2: The ‘Location’ category with its sub-categories and the metrics used 23](#_Toc52722800)

[Figure 3: Each sub-category would feature demographics intersection performances too 24](#_Toc52722801)

[Figure 4: The ‘Gender’ category 25](#_Toc52722802)

# Introduction

An estimated 3.6 billion diagnostic medical examinations, such as X-rays, are performed worldwide every year. Advances in radiology technology have improved illness and injury diagnosis and treatments. These radiological procedures include X-Rays, Mammograms, Ultrasound, PET (positron emission tomography) scans, MRI (magnetic resonance imaging) scans and CT (computed tomography) scans. They are used mainly in dealing with a broad range of non-communicable or chronic diseases. These are primarily cardiovascular diseases, cancer, chronic respiratory diseases and diabetes. Radiology has helped in the rapid non-invasive screening of conditions such as breast cancer, which reduces the mortality rate, especially with early detection. 33 million screening mammography exams are performed each year in the United States alone. Research led by Elizabeth Kagan Arleo, MD, of Weill Cornell Medicine found that recommendation of annual screening starting at age 40 would result in a nearly 40 percent reduction in deaths due to breast cancer (Arleo et al, 2017). Simple radiological procedures like ultrasound can reduce the need for surgical interventions. And though clinical judgement may be sufficient, radiological procedures are necessary in confirming and properly evaluating the causes of many conditions and responses to treatments.

## Document Structure

Overview of the whole document.

## Topic Description

**Challenges Facing Radiology**

Though radiology is very important, there’s a shortage of radiologists globally, especially in developing countries. Liberia, for example, only has about 2 radiologists (RAD-AID, 2017), whilst Ghana has 34 radiologists and Kenya has 200 radiologists (UCSF, 2015). And in the UK, only one-in-five trusts and health boards has sufficient number of interventional radiologists to run a safe 24/7 service to perform urgent procedures (Clinical Radiology UK Workforce Census Report, 2018) whilst their workload of reading and interpreting medical images has increased by 30% between 2012 and 2017. There’s a need for scalable and accurate automated radiological systems. Deep Learning, especially Convolutional Neural Networks, is gaining wide attention for its ability to accurately analyse medical images, with the potential to help solve the shortage of radiologists.

**Artificial Intelligence in Radiology**

The re-emergence of Artificial Intelligence (A.I) and Deep Learning, due to growth in computing power and data, has led to advancements in Deep Convolutional Neural Networks, which has allowed for breakthrough research and applications in Radiology. Artificial Intelligence and Deep Learning holds a lot of potential in Radiology. Artificial Intelligence can provide support to radiologists and alleviate radiologist fatigue. It can help in flagging patients who require urgent care to radiologists and physicians. Deep Learning could also help increase interrater reliability among radiologists throughout their years in clinical practice. A recent study found that the Fleiss’ kappa measure of interrater reliability for detecting anterior cruciate ligament tear, meniscal tear, and abnormality were higher with model assistance than without it (Bien et al., 2018). Deep Learning has achieved performances comparable to humans and sometimes better. A recent study analysed 14 research works done using Deep Learning to detect diseases via medical images, they found that on average, Deep Learning systems correctly detected a disease state 87% of the time – compared with 86% for healthcare professionals – and correctly gave the all-clear 93% of the time, compared with 91% for human experts (Liu et al., 2019). Deep Learning has performed as well as radiologists and sometimes better at detecting abnormalities like pneumonia, fibrosis, hernia, edema and pneumothorax in chest x-rays (Rajpurkar et. al, 2017). It has also been used to detect knee abnormalities via magnetic resonance (MR) imaging at near-human-level performance (Bien et. al, 2018). Researchers have also trained Deep Learning models that outperformed dermatologists at detecting skin cancer (Esteva et. al, 2017, Haenssle et. al, 2018).

**Research Data**

One key focus of deep learning radiological applications is breast cancer detection via mammograms. The CBIS-DDSM (Curated Breast Imaging Subset of Digital Database for Screening Mammography) is one of the key repositories publicly available. It contains 10,239 images and is grouped under the labels; Benign, Benign Without Callback and Malignant. Another set of focus is the detection of thoracic conditions via chest x-rays. One publicly available chest x-Ray dataset is CheXpert by the Stanford University School of Medicine. CheXpert contains 224,316 chest radiographs of 65,240 patients. It contains images for 12 different thoracic diseases including Atelectasis, Cardiomegaly, Enlarged Cardiomegaly, Consolidation, Edema, Lung Lesion, Lung Opacity, Pneumonia, Pneumothorax, Fracture, Pleural Effusion and Pleural Other. And it contains 2 other observations “No Finding” and “Support Devices”, making 14 observations in total. The radiographs were collected from Stanford Hospital, between October 2002 and July 2017. Another publicly available chest radiograph dataset is MIMIC-CXR dataset by Massachusetts Institute of Technology (MIT). The dataset contains 371,920 chest x-rays associated with 227,943 imaging studies. Each imaging study contains a frontal view and a lateral view. MIMIC-CXR dataset also contains 14 observations. There is also a chest x-ray dataset from the NIH Clinical Center that contains 100,000 x-rays from over 30,000 patients, including many with advanced lung disease. That leads to a total of 696,236 publicly available x-ray images for 12 thoracic conditions.

**Challenges Facing AI in Radiology**

The challenge however lasts in properly testing such systems and ensuring they work in all edge and diverse cases radiologists encounter. A study by Eric Oermann and colleagues found that, deep learning models that detected pneumonia on chest x-rays performed well on further data from sites they were trained on (AUC of 0.93–0.94) but significantly less on external data (AUC 0.75–0.89) (Zech et al., 2018). This demonstrates the challenge of assessing the generality and scalability of Deep Learning systems. Though the study by Liu and colleagues analysed 31,587 studies, only 69 studies provided enough data to construct contingency tables, enabling calculation of test accuracy. And out of that 69 studies, only 25 studies did out-of-sample external validations. And further, only 14 of such studies compared the models’ performances to that of radiologists. They also realised the methodology and reporting of studies evaluating deep learning models is variable and often incomplete. This shows the need for standardization of evaluation frameworks and benchmarks for AI radiological systems. This is essential to assessing the quality of Artificial Intelligence solutions, their readiness to be deployed and the degree of autonomy they should be given.

### Impact of Benchmarking

There exists a large amount of publicly available medical image datasets online, and there have been a lot of research and development with such datasets. By developing frameworks that target these conditions first, we would make the standardized benchmarking platform immediately appealing to the A.I healthcare research and development community. This would also help speedup the deployment of AI solutions in Radiology globally. AI healthcare system developers and organisations usually have to go through the challenge of convincing health facilities to share their private data with them, such data unfortunately aren’t always of high quality and they usually lack the broad demographic representations needed to truly assess how well an A.I system generalises. A radiograph-agnostic benchmarking platform with data from various facilities across the globe, reviewed by a panel of experts to ensure quality and diversity, would drastically simplify the evaluation stage of such AI systems. The ‘Precision Evaluation’ framework would help fight against demographically biased A.I systems by ensuring they are tested in great detail across various groups. It’d also help in the safe scaling of AI systems across different locations. The ‘Location’ sub-categorization of evaluation allows for ‘Geo-Precision Evaluation’. Developers can tell how well their systems can perform within their country or first-point of deployment, and should they intend to scale to neighbouring countries then eventually have it across the globe, they can tell how well their current version would perform at each point of such growth and scaling.

## Ethical Considerations

* ethical considerations on usage of AI
* ethical consideration of and benchmarking including its data acquisition

## Existing AI Solutions

### Use Case Descriptors

To collect existing AI solutions and use cases, we identified the following 9 descriptors that would be useful:

* Condition
* Medical imaging modality
* AI task/problem description (e.g. Image Classification, Image Segmentation)
* General algorithm description (if shareable)
* Project goal and current stage (if shareable)
* Input structure and format
* Output structure and format
* Evaluation metrics
* Explainability and Interpretability framework

### Collected AI solutions and use cases

|  |  |
| --- | --- |
| minoHealth |  |
| **Descriptor** | **Description** |
| **Condition** | Pneumonia, Hernia, Fibrosis, Atelectasis, Cardiomegaly, Enlarged Cardiomegaly, Consolidation, Edema, Lung Lesion, Lung Opacity, Pneumothorax, Fracture, Pleural Effusion and Pleural Other (14 different systems) |
| **Medical imaging modality** | Chest XRay |
| **AI task/problem description** | Image Classification |
| **General algorithm description** | Convolutional Neural Networks, Transfer Learning |
| **Project goal and current stage** | Commercial, Testing and Piloting. |
| **Input structure and format** | 2D image, jpeg (converted from DICOM) |
| **Output structure and format** | Sigmoid with range 0 - 1, 0 = Negative, 1 = Positive |
| **Evaluation metrics** | Accuracy Score, ROC curve & Area Under Curve Score |
| **Explainability and Interpretability framework** | Implementing LIME |

|  |  |
| --- | --- |
| minoHealth |  |
| **Descriptor** | **Description** |
| **Condition** | Breast Cancer |
| **Medical imaging modality** | Mammograms |
| **AI task/problem description** | Image Classification |
| **General algorithm description** | Convolutional Neural Networks, Transfer Learning |
| **Project goal and current stage** | Commercial, Testing and Piloting. |
| **Input structure and format** | 2D image, jpeg (converted from DICOM) |
| **Output structure and format** | Softmax with 3 classes, Benign, Benign Without Callback and Malignant |
| **Evaluation metrics** | Accuracy Score, ROC curve & Area Under Curve Score |
| **Explainability and Interpretability framework** | Implementing LIME |

|  |  |
| --- | --- |
| Braid.Health |  |
| **Descriptor** | **Description** |
| **Condition** | Atelectasis, Cardiomegaly, Consolidation, Edema, Effusion, Emphysema, Fibrosis, Hernia, Infiltration, Mass, Nodule, Peural\_Thickening, Pneumonia, Pneumothorax, Old Fracture, New Fracture, Scoliosis, Sternotomy, Enlarged Cardiomedistinum, Support Devices, Tuberculosis, Bronchiectasis, Foreign Body (22 conditions) |
| **Medical imaging modality** | Chest XRay |
| **AI task/problem description** | Image Classification |
| **General algorithm description** | Convolutional Neural Networks, DenseNet 121, Transfer Learning, Bayesian Optimization, Strong Augmentations |
| **Project goal and current stage** | Commercial, Testing and Piloting. |
| **Input structure and format** | 2D image, PNG (converted from DICOM) |
| **Output structure and format** | Calibrated score from 0.0 to 1.0 representing Precision of data for the current distribution |
| **Evaluation metrics** | ROC curve, Area Under Curve ROC Score, Specificity at Sensitivity |
| **Explainability and Interpretability framework** | None currently |

|  |  |
| --- | --- |
| Braid.Health |  |
| **Descriptor** | **Description** |
| **Condition** | Fracture, Dislocation, Edema, Arthritis, Osteoarthritis, Spur (6 conditions) |
| **Medical imaging modality** | Foot XRay |
| **AI task/problem description** | Image Classification |
| **General algorithm description** | Convolutional Neural Networks, DenseNet 121, Transfer Learning, Bayesian Optimization, Strong Augmentations |
| **Project goal and current stage** | Commercial, Testing and Piloting. |
| **Input structure and format** | 2D image, PNG (converted from DICOM) |
| **Output structure and format** | Calibrated score from 0.0 to 1.0 representing Precision of data for the current distribution |
| **Evaluation metrics** | ROC curve, Area Under Curve ROC Score, Specificity at Sensitivity |
| **Explainability and Interpretability framework** | None Currently |

|  |  |
| --- | --- |
| minoHealth |  |
| **Descriptor** | **Description** |
| **Condition** | Chest\_AP, Chest\_LAT, Chest\_PA, Foot\_AP, Foot\_LAT, Foot\_OBL, Ankle\_AP, Ankle\_LAT, Ankle\_OBL, Hand\_LAT, Hand\_OBL, Hand\_PA, Knee\_AP, Knee\_LAT, Knee\_OBL, Knee\_SUNRISE, Wrist\_LAT, Wrist\_OBL, Wrist\_PA, Wrist\_SCAPHOID, Abdomen\_AP, Abdomen\_SUPINE, Finger\_LAT, Finger\_OBL, Finger\_PA, Toe\_AP, Toe\_LAT, Toe\_OBL, Shoulder\_AP, Shoulder\_EXTERNAL, Shoulder\_INTERNAL, Shoulder\_Y-VIEW, Elbow\_AP, Elbow\_LAT, Elbow\_OBL, Forearm\_AP, Forearm\_LAT, Ribs\_AP, Ribs\_LOWER, Ribs\_UPPER, Lumbar\_Spine\_AP, Lumbar\_Spine\_L5-S1, Lumbar\_Spine\_LAT, Cervical\_Spine\_AP, Cervical\_Spine\_LAT, Cervical\_Spine\_ODONTOID, Thoracic\_Spine\_AP, Thoracic\_Spine\_LAT, Thoracic\_Spine\_SWIMMERS, Clavicle\_AP, Hip\_AP, Hip\_LAT, Pelvis\_AP, Humerus\_AP, Humerus\_LAT, Unknown (56 classes) |
| **Medical imaging modality** | XRay |
| **AI task/problem description** | Image Classification |
| **General algorithm description** | Convolutional Neural Networks, DenseNet 121, Transfer Learning, Bayesian Optimization, Strong Augmentations |
| **Project goal and current stage** | Commercial, Testing and Piloting. |
| **Input structure and format** | 2D image, PNG (converted from DICOM) |
| **Output structure and format** | Calibrated score from 0.0 to 1.0 representing Precision of data for the current distribution |
| **Evaluation metrics** | ROC curve, Area Under Curve ROC Score, Specificity at Sensitivity |
| **Explainability and Interpretability framework** | None currently |

## Imaging Modalities

We map out the various medical imaging modalities. The goal of this work is to identify each imaging modality, address how AI can be used with such modality towards diagnosis, triage, forecasts, prognosis or treatment of certain conditions.

Each modality would have paragraphs dedicated to covering details using the pointers below:

* Description: Description of imaging modality
* Conditions: Conditions modalities are applied to
* Data structure: Data structure of images from modality   
  This would cover some details on the type of images generated from each modality. These details would include whether it’s a single/multiple 2D image or 3D image, DICOM or some other format
* AI Applications: How AI is being used with modality

**Table 1: Imaging Modalities**

|  |  |
| --- | --- |
| **Conventional radiography (plain x-rays)** |  |
| Description | Radiography is the use of x-rays to visualize the internal structures of a patient. X-Rays are a form of ionizing electromagnetic radiation, produced by an x-ray tube using a high voltage to accelerate the electrons produced by its cathode. The produced electrons interact with the anode, thus producing x-rays. The x-rays are passed through the body and captured behind the patient by a detector; film sensitive to x-rays or a digital detector. Different soft tissues attenuate x-ray photons differently, depending on tissue density; the denser the tissue, the whiter (more radiopaque) the image. The range of densities, from most to least dense, is represented by metal (white, or radiopaque), bone cortex (less white), muscle and fluid (gray), fat (darker gray), and air or gas (black, or radiolucent). This variance produces contrast within the image to give a 2D representation of all the structures within the patient [1,2]. |
| Conditions | Typically, conventional radiography is the first imaging method indicated to evaluate the extremities, chest, and sometimes the spine and abdomen.  Chest: to assess lung pathology, e.g., atelectasis, pneumonia, pulmonary edema, heart failure, solitary pulmonary nodule, lung masses, diffuse lung diseases, pleural diseases.  Skeletal: to examine bone structure and diagnose fractures, dislocation or other bone pathology.  Abdomen: can assess abdominal obstruction, free air or free fluid within the abdominal cavity [1,3]. |
| Data structure | Single/multiple 2D image. |
| AI Applications | * Different AI approaches have been proposed to segment chest anatomical structures such as lungs, heart, and clavicle bones, for diagnostic purposes [4]. * AI has also been developed to classify normal and abnormal results from chest radiographs with major thoracic diseases including cardiomegaly, pulmonary malignant neoplasm, active tuberculosis, interstitial lung diseases, pneumothorax, pulmonary edema, emphysema, pneumonia, and pediatric pneumonia [5–15]. * For COVID-19 patients, new AI approaches focusing on detection, classification, segmentation, stratification and prognostication are showing encouraging results [16–22]. AI has been proposed to allow for lung disease severity staging. Deep-learning convolutional neural network (CNN) accurately stages disease severity on portable chest x-ray of COVID-19 lung infection [23]. It has also been proposed that deep learning can thus help support the diagnosis of heart failure using chest X-ray images [24]. * Bone suppression techniques based on artificial intelligence have been developed to avoid overlooking lung nodules because of bones overlapping the lung fields [25]. * AI has been used for analysis and features extraction of spine X-ray images, which may allow prediction of high-risk populations with abnormal bone mineral density [26]. Application prospects have also been described in bone age assessment [14,27]. * In the field of orthopaedics, an AI model can automatically measure Sharp's angle as observed on pelvic x-ray images to aid diagnosis of developmental dysplasia of the hip [28]. It has also been shown the utility of deep learning in detecting hip, pelvic and acetabular fractures with pelvic radiographs [29]. Collection, processing, and integration of pre-, intra-, and postoperative multimodal imaging data could be performed in a more efficient and accurate manner, which has been proposed could then be incorporated into robot-assisted orthopaedic surgery system [30], as well as for numerous X-ray-guided procedures [31]. |
| **Fluoroscopy** |  |
| Description | Fluoroscopy is a technique, usable as a standalone technique or in concert with others, that utilizes a continuous X-ray beam throughout a target in a subject’s body to study both its structure and movement and can be applied to single organs or a system of them [35-37] |
| Conditions | This modality is commonly applied to conditions that involve foreign bodies, obstruction or modification of fluid transport, or fractures[35-37] |
| Data structure | Images generated through fluoroscopy can be produced in single-plane 2D images as well as multi-plane 3D images [35-37] |
| AI Applications | AI is being used to simplify and optimize presentation of imaging, as well as reduce radiation exposure to patients [38-39] |
| **Angiography** |  |
| Description | Angiography is a medical imaging modality that focuses on imaging the inside of blood vessels and organs. In angiography, a contrast medium is injected into the blood vessel and the path of the tracer or contrast medium is imaged using X-ray. [57][58] |
| Conditions | Some conditions angiography is applied to are: diagnosis of obstructive vascular disease, diagnosis of aneurysms, diagnosis of arterio-venous malformations, diagnosis of bleeding vessels, and assessment of vascularity of malignant tumors. [57] |
| Data structure | Angiograms can be 2D or 3D image files |
| AI Applications | AI is used in post processing tasks like segmentation.  Also AI is used to perform certain calculations like calculating calcium score and fraction flow reserve (FFR). [59] |
| **Mammography** |  |
| Description | Mammography is a medical imaging modality that uses low energy X-rays to image the human breast. Mammography is mostly used for early detection of breast cancer. Its mode of operation is very similar to that of the conventional X-ray machine, except that it employs low power radiations. [49][50] |
| Conditions | Mammography can be used as a screening tool or a diagnostic tool.   * As a screening tool, mammography is used for the early detection of breast cancer. * As a diagnostic tool, mammography is used to investigate abnormal clinical findings in the breast, like breast lumps and nipple discharge. [50] |
| Data structure | Mammograms may be 2D or 3D image files. [50] |
| AI Applications | AI, in combination to radiologists, is used to improve the accuracy of breast cancer screening. [51] |
| **Computed Tomography (CT)** |  |
| Description | Computed Tomography (CT) also called computed axial tomography, is a non-invasive imaging method that uses X-rays, combined with computing to produce cross-sections of subjects, allowing for highly detailed models of patients or areas of interest to study; patients are sometimes given a contrasting material to improve image quality [72-73]. |
| Conditions | CTs are used in multiple diagnostic works and therapies, and have additional value in that full body scans are possible [72-73]. Examples of uses include disease diagnosis and prognosis, guidance of medical procedures, and treatment monitoring across a wide spectrum of disorders from problems with vasculature, bone fractures, investigations in oncology, psychiatry and more [72-75]. It has even found use in investigating complications associated with Covid-19 within patients [76-77]. |
| Data structure | CT scans take numerous 2D images, and these can be used to make 3D representations, thus allowing 2D and 3D formats [72,84]. |
| AI Applications | Current AI uses extend from use of CT-images, but is also expanding through investigation of AI-Assisted smart tools to guide and upgrade the use of Ct scans through improved diagnosis, measurements, and prognoses [78-82]. It is believed that future uses can entail more comprehensive reconstructions of scanned areas and less radiation use though less coregistration of CTs with other imaging means, helping to reduce patient fatigue and exposure; more may abound as this area of research, that is the combination of AI and CT scanning, is still new [83]. |
| **Single-photon emission computed tomography (SPECT)** |  |
| Description | Single photon emission computed tomography (SPECT) is a technique which allows nuclear medicine studies, which would otherwise be represented in planar images, to be rendered in three dimensions. Photons emitted by injected radiopharmaceuticals are detected by gamma cameras which rotate around the patient to provide spatial information on tissue distribution. The data is then reconstructed into three-dimensional images. SPECT can also be combined with conventional CT (SPECT-CT) to allow accurate attenuation correction for the purposes of reconstruction, and to provide additional anatomical information. |
| Conditions | The technique can theoretically be applied to any nuclear medicine studies, but it is not required in every situation. SPECT is commonly used in the context of technetium-99m sestamibi scans when evaluating the perfusion of the cardiac myocardium or the function of parathyroid glands. It is also used in the context of technetium methylene diphosphonate (MDP) bone scans which provide information about bone perfusion and turnover. |
| Data structure |  |
| AI Applications |  |
| **Ultrasonography (US) and Doppler** |  |
| Description | Ultrasonography is an imaging modality that uses ultrasound (sound waves with frequencies greater than frequencies that are audible to the human ear) to create images of internal body parts. The ultrasound is sent into the body by a transducer and echoes from tissue interference are recorded to create an image of the structure under examination. [40] |
| Conditions | Ultrasound imaging is used to examine an organ whenever there is a symptom of pain, swelling or infection in that organ. Ultrasonography can be used to image the liver, kidney, heart, pancreas, etc. [41][42]  Another common use case for ultrasonography is real-time imaging of developing fetuses in pregnant mothers. |
| Data structure | Sonograms may be stored as a single layer 2D image.  Multiple 2D sonograms may also be projected into a 3D image  An additional time dimension can be added to a 3D sonogram to create a 4D sonogram.[43] |
| AI Applications | AI is used to perform a wide range of tasks in ultrasonography. These tasks include image classification, segmentation, detection, registration, biometric measurements and quality assessment. [44] |
| **Magnetic resonance Imaging (MRI)** |  |
| Description | Magnetic resonance imaging is an imaging modality that uses a strong magnetic field to create images of the internal structures of the body. The strong magnetic field forces protons of water molecules in the body to align with the field. When a radiofrequency current is passed through the patient, the alignment of the protons is disturbed. When the radiofrequency current is turned off, the protons return to equilibrium with the magnetic field and the MRI sensors detect the energy released by the protons as they return to equilibrium. Unlike the CT or conventional X-ray, MRI does not employ any ionizable radiation, so it is safer and can be taken more frequently. [52][53] |
| Conditions | MRI is suitable for imaging soft tissues like muscles, tendons, ligaments, brain, joints, the abdomen, etc.  MRI is also employed in image guided interventional procedures [52][54] |
| Data structure | MRI images can be 2D or 3D image files |
| AI Applications | AI is used to correct artifacts in MRI scans [55]  AI is also used to classify MRI scans as healthy or diseased. [56] |
| **Nuclear Medicine Imaging** |  |
| Description | Nuclear medicine imaging is an imaging modality that involves the injection or inhalation of small amounts of radioactive compounds (called radiotracers) into the body to visualize organs in the body. The radiotracers are organ specific and they emit gamma rays when they arrive at the target organ. The emitted gamma rays are captured and visualized using a gamma camera. Nuclear medicine imaging is considered as an “inside out” radiology, because it records radiations generated from the body rather than an external source like an X-ray. [45][46][47] |
| Conditions | This modality is applicable to conditions that require an assessment of the physiology of organs. Some organs that are commonly assessed using nuclear imaging are kidney, lungs, heart, thyroid gland, and bone. [45] |
| Data structure | Nuclear images could be 2D images (scintigraphy) or 3D images (SPECT). Some modern nuclear imaging equipment are hybrid and allow for a fusion between CT and nuclear imaging. [45][47] |
| AI Applications | In nuclear imaging, AI is commonly used for radiomics.  AI could potentially be used to detect artifacts and noise in nuclear images and correct them by applying the appropriate algorithm. |
| **Positron emission tomography (PET)** |  |
| Description | Positron Emission Tomography (PET) is an imaging modality that uses a tracers, or radioactive drugs, to image the function of tissues of organs [32] |
| Conditions | PET is used for diagnosis and staging in oncology, in addition to observing specific neurological and cardiovascular issues[33]. |
| Data structure | Images can come in 2D or 3D modalities. [34]. |
| AI Applications | AI has been documented in use with PET for distinguishing between benign and malignant nodules, as well as detection and quantification of nodules[35,60].Future developments may improved correlation of image features with clinical end points, correction of images, reduction of doses needed for reliable scans, guided use, and improved reconstructions[83, 85]. These together can result in savings and improved patient outcomes, with more to abound as research in this area is still new. |
| **Interventional Radiology** |  |
| Description | Interventional Radiology (IR) is a means of radiology that uses current imaging methods, such as CTs,MRIs,,X-rays, PETs, and Ultrasound, led by teams of professionals to treat the source of diseases in a non-invasive or minimally invasive manner. A subset, interventional oncology [IC] is used to address cancer [61] |
| Conditions | (IR) is used for diagnosis and guiding of treatment across cardiology, neurology, nephrology, oncology, and more [61]. |
| Data structure | Image modalities from IR depend on the imaging methody combinations as described in the sections above. |
| AI Applications | AI has been used in IR to predict treatment outcomes for treatments like chemoembolization, incidents like a post-treatment stroke, or offer prognostic information on brain malformations [63-65]. Gesture capture, voice recognition, implement/tool guidance, and Augmented reality have been employed to assist efforts across various tasks [66-69]. A smart assistant has been trialed, but more details await [70,71]. Applications that improve features such as segmentation of subjects, improved lesion detection, prognostic information gathering, interpretation, reduction of waste, and improved cost-benefit analyses are imagined in the future of IR with AI. [62,70-71] |

## Existing work on benchmarking

* papers on existing attempts to benchmark solutions on the topic
* clinical evaluation attempts, RCT, etc.
* including existing numbers

# AI4H Topic group

* Topic group structure
* Subtopic 1
* Subtopic 2
* Topic group participation
* Tools/process of TG cooperation: Slack, Zoom, Google Docs, Github
* TG interaction with WG, FG: Work in DAISAM and DASH to test frameworks in Sandbox
* Current topic group and topic status
* Contributors so far
* Next meetings
* Next steps for the work on this document

# Method

* Overview of the benchmarking

## AI Input Data Structure

* possible inputs for benchmarking
* ontologies, terminologies
* data format

### Image Conversion Considerations

For use cases that require image conversions like DICOM to JPEG before being used as input for an AI system, manufacturers should ensure input data integrity and quality is maintained.

Currently, there are a number of approaches available to convert DICOM to JPEG.

**Table 2: Image Conversion Considerations**

|  |  |  |
| --- | --- | --- |
| **Conversion Approach** | **Advantages** | **Disadvantages** |
| **Integrating an automated conversion programme into AI Software.**  It is also possible to use python tools pydicom and opencv-python to automate the process of converting DICOM to jpeg within the software platform, in that case, the users wouldn't have to worry about the conversion. | * Easier for users in clinical settings * Conversion cannot be easily interfered. * Leaves little room for error on the part of users | * Requires further development of by manufacturers * Subjected to the quality of manufacturers’ software development |
| **Using a separate software.**  There's MicroDicom, a free windows tool, and a number of other tools that are either free or must be paid for. | * Easier for manufacturer since it requires no to little additional development * Can allow for reliance on already established and trusted high-quality tool * If offline, it can ensure data privacy better than an online tool. | * Requires additional procedures from users to use AI software * Prone to errors and incorrect input data if misused * Creates avenue for third party interference |
| **Using an online tool.**  There are also online free tools, like: <https://www.onlineconverter.com/dicom-to-jpg> | * Easier for manufacturer since it requires no to little additional development * Can allow for reliance on already established and trusted high-quality tool | * Requires additional procedures from users to use AI software * Prone to errors and incorrect input data if misused * Creates avenue for third party interference * Can allow online tool manufacturers to have unauthorised access to data. |

## AI Output Data Structure

* outputs to benchmark
* ontologies, terminologies
* data format

## Test Data Labels

* label types
* ontologies, terminologies
* data format

## Scores & Metrics

The taxonomy used in grouping these evaluation metrics is that which was proposed by Cesar Ferri, et al. in their 2008 paper titled “An Experimental Comparison Of Performance Measures For Classification.”

* Threshold Metrics
* Ranking Metrics
* Probability Metrics.
  + 1. **Threshold Metrics**
       1. **Accuracy Metrics**

**Classification Accuracy**

This is the fraction of correct predictions of a model. It is however not suitable for imbalanced classification because a poorly fitted model that simply predicts the majority class would end up having a misleading high score.

**Classification Error**

This measure is the inverse of classification accuracy. It is the fraction of incorrect predictions of a model. It is also not suitable for imbalance classification.

**Patient Level Accuracy & Image Level Accuracy**

The patient level accuracy metric is defined as follows. For each patient, let *Nt*

be the total number of images and *Nc* the number of images correctly classified,

then patient score S can be defined as:

Therefore, the patient level accuracy can be calculated as

Where *T* is the total number of patients.

The image level accuracy measures the rate of correctly classified images to

the total number of images in the dataset. Let *N* be the total number of images

in testing data and *C* the number of correctly classified images.

* + - 1. **Sensitivity-Specificity Metrics**

**Sensitivity**

This is the true positive rate. It measures the proportion of positive samples correctly predicted by a model.

**Specificity**

This is the true negative rate. It measures the proportion of negative samples correctly predicted by a model.

**Geometric mean (G-Mean)**

The geometric mean metric is the square root of the product of the sensitivity (true positive rate) and specificity (true negative rate) scores of a model.

* + - 1. **Precision-Recall Metrics**

**Precision**

Precision is a metric that computes the fraction of true positive predictions among the outcomes that the model classified as positive.

**Recall**

Recall, also known as sensitivity, is the fraction of examples classified as positive, among all total numbers of positive examples. In other words, the number of true positives divided by the number of true positives plus false negatives.

**F-Measure**

F-measure provides a way to combine precision and recall into a single score. It is the harmonic mean of two fractions. It is sometimes called the F score or F1 score. It is the most popular metric for working with imbalanced datasets.

**Fbeta-Measure**

Fbeta measure is an abstraction of f-measure score. A coefficient called beta is used to control the calculation of the harmonic mean of the precision and recall.

**Matthews Correlation Coefficient (MCC)**

The **Matthews correlation coefficient** (MCC) or phi coefficient is a measure of the quality of binary (two-class) classifications. MCC according to Chicco [6] is more informative than F1 score and accuracy score in evaluating binary classification problems, because it produces a high score only if the prediction obtained good results in all of the four confusion matrix categories (true positives, false negatives, true negatives, and false positives), proportionally both to the size of positive elements and the size of negative elements in the dataset.

where is the total number of observations.

MCC could also be calculated directly from the confusion matrix as;

Where is the number of True Positives, is the number of True Negatives, is the number of False Positivesis the number of False Negatives

* + 1. **Ranking Metrics**

**Receiver Operating Characteristic (ROC) Curve**

The ROC curve is a graphical plot used to summarise the diagnostic ability of a classification model. It is created by plotting the true positive rate (sensitivity) against the false positive rate (1 − specificity). It was created primarily for binary classification, but it can be generalised for multiclass classification. The area under the curve (AUC) can be calculated and used as a single score to summarise the performance of a model.

**Precision-Recall Curve**

Precision-Recall curve is also a graphical plot used to summarise the diagnostic ability of a classification model. ROC curves can be misleading with an imbalanced dataset, especially when the ‘negative’ samples are small. A poorly fitted model that simply predicts positive can end with a high AUC score, which would be misleading. In such a scenario, the precision-recall curve and area under the curve could be used. It is created by plotting the precision score against the recall score (sensitivity).

* + 1. **Probability Metrics**

**Logarithmic loss or Cross-entropy**

Cross-entropy is a measure of the difference between two probability distributions. A lower score implies a better model, with 0.0 being the best. Log-loss is defined as;

Cross Entropy =

where andare the groundtruth and the model’s score for each classin

**Brier Score**

The Brier score is calculated as the mean squared error between the expected probabilities for the positive class (e.g. 1.0) and the predicted probabilities. [Src](https://machinelearningmastery.com/tour-of-evaluation-metrics-for-imbalanced-classification/) It ranges between 0.0 and 1.0.

BrierScore =

where expected values are and the predicted values are

**Brier Skill Score**

In order to more appropriately compare the brier score of different models, the brier score can be scaled against a reference, such as the score of no skill model.

BrierSkillScore =

## Undisclosed Test Data Set Collection

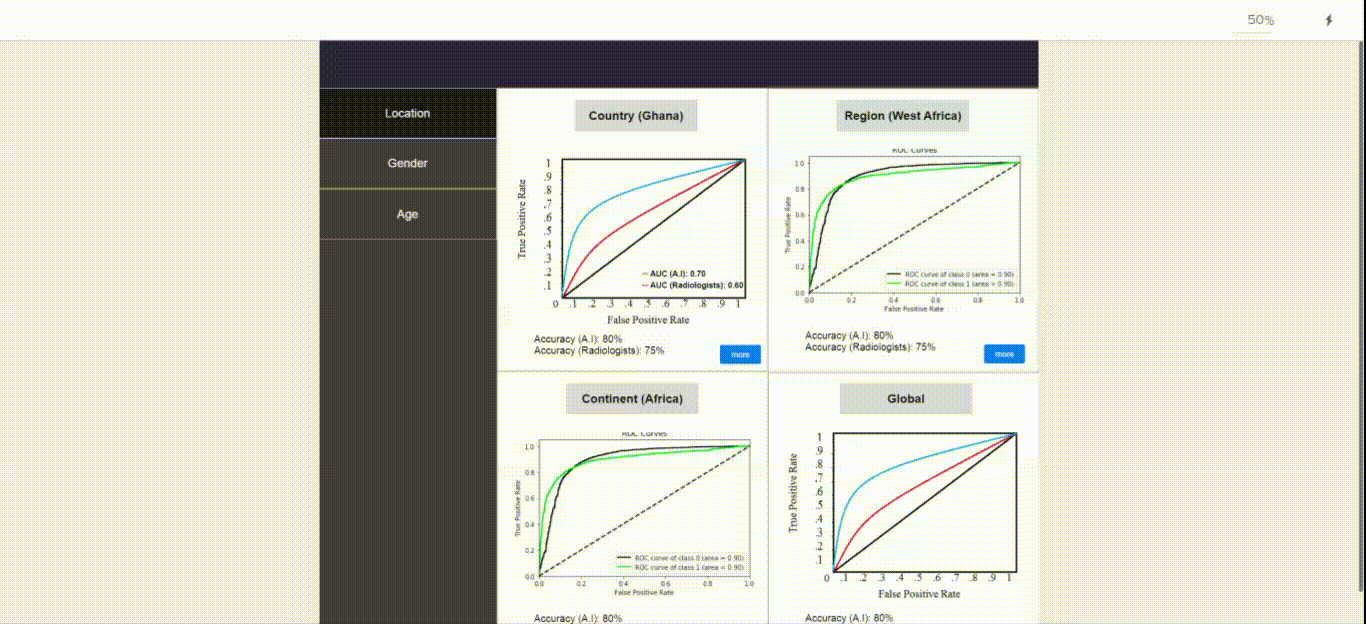
* raw data acquisition / acceptance
* test data source(s): availability, reliability,
* labelling process / acceptance
* bias documentation process
* quality control mechanisms
* discussion of the necessary size of the test data set for relevant benchmarking results
* specific data governance derived by general data governance document (currently C-004)

## Benchmarking Methodology and Architecture

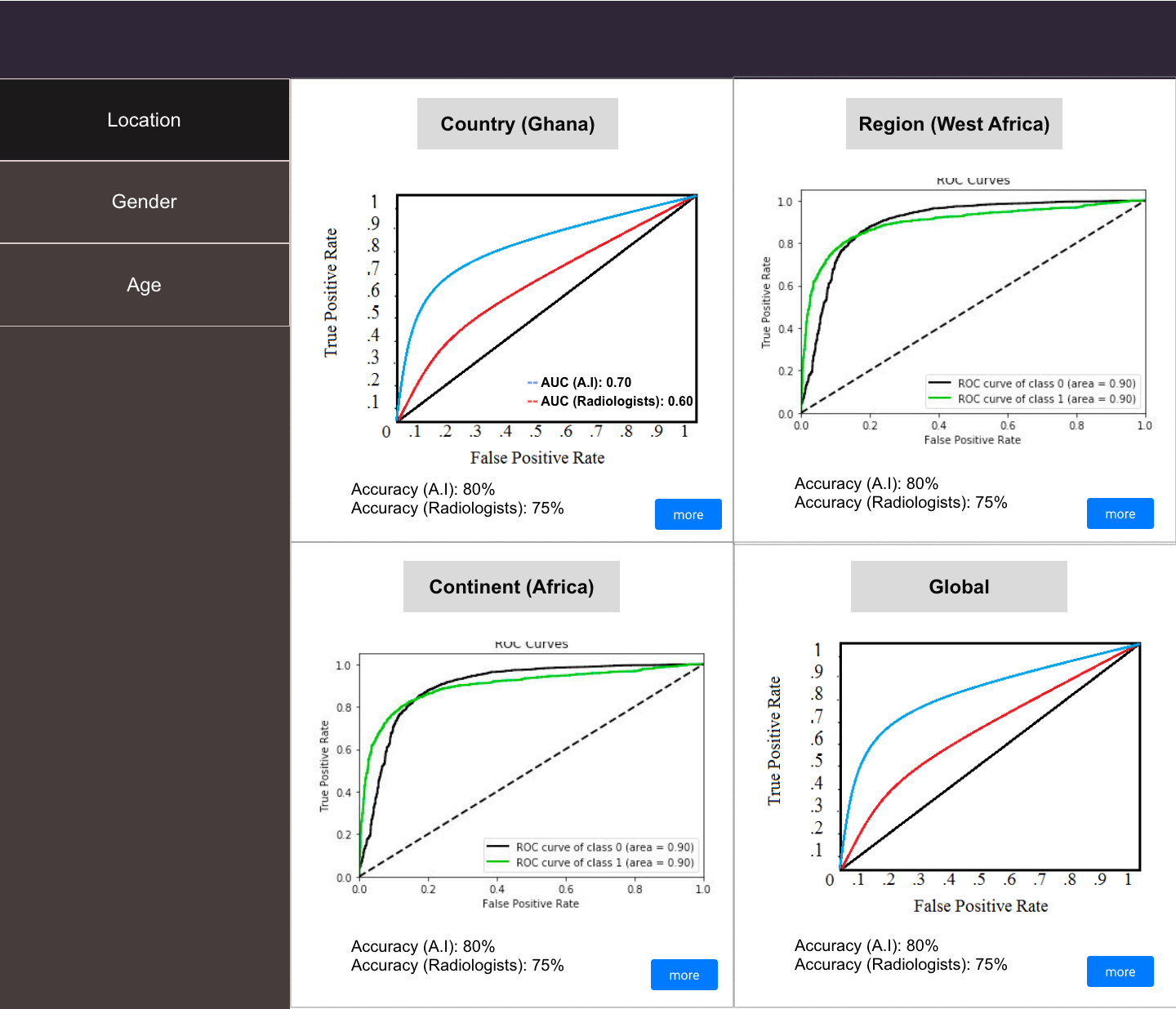
* technical architecture
* hosting (IIC, etc.)
* possibility of an online benchmarking on a public test dataset
* protocol for performing the benchmarking (who does what when etc.)
* AI submission procedure including contracts, rights, IP etc. considerations

### Benchmarking Solution

We are proposing a radiograph-agnostic benchmarking platform and framework that would allow for the evaluation of AI radiological systems for various conditions and serve as a standard. This would require registered developers and organisations seeking to evaluate their A.I system to download the test images and a csv file with two columns; ‘ID’, containing the unique Identification of each test image and ‘Class’ which would be left blank in order to be populated by the outputs of an A.I system. Developers are then to submit the fully populated csv file, which would then provide the model’s outputs to be evaluated with the true labels. Tutorial scripts in popular Machine Learning libraries and frameworks would be provided to developers on how to correctly get your model’s outputs to be populated in the csv file.



**Figure 1: A prototype of the radiograph-agnostic precision evaluation platform.**

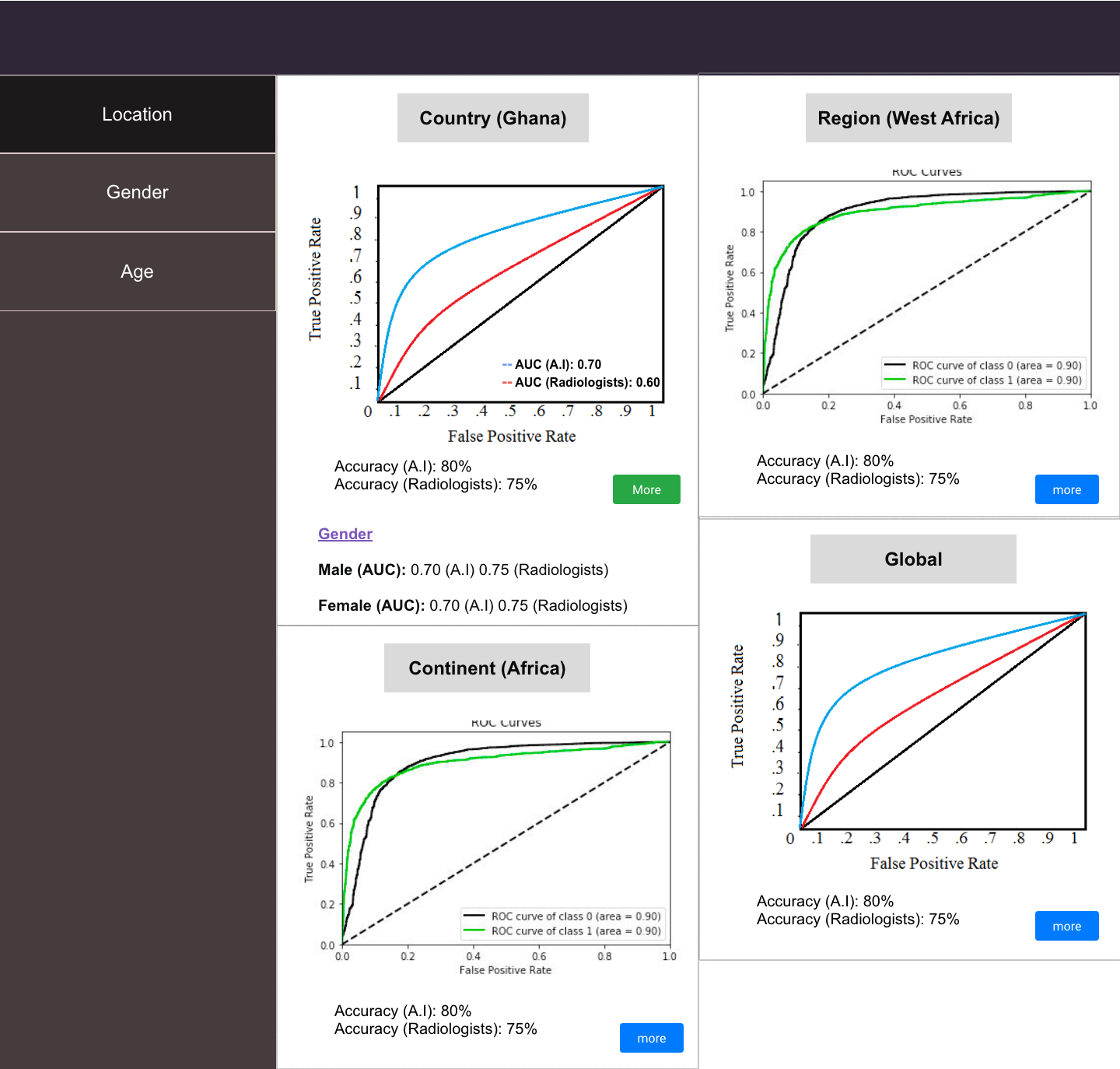


**Figure 2: The ‘Location’ category with its sub-categories and the metrics used**

### Evaluation Metrics

All our supported condition tests on the platform would be image classification tasks and therefore we would be using evaluation metrics for classification. Some of the conditions and tests would be binary classification tasks while others would be multi-class classification, therefore we would be using metrics that can be used for both types of classification. As shown in Figure 1 and Figure 2, the evaluation metrics to be used would be the Receiver Operating Characteristic (ROC) curve, its Area Under the Curve (AUC) score and the Accuracy Score. The ROC curve and AUC score would help us identify the model’s true positive rate (TPR) (Sensitivity) and its false positive rate (FPR) (1 - Specificity). Though originally for binary classification, the ROC curve and AUC score can be generalised to multi-class classification.

The performance of an A.I system would be compared with radiologists using the various metrics. This would help developers see how well their models perform compared to the current popular approach, standalone radiologists. Benchmarking vis-à-vis radiologists would also help in assessing the level of autonomy that should be given each A.I system.



**Figure 3: Each sub-category would feature demographics intersection performances too**

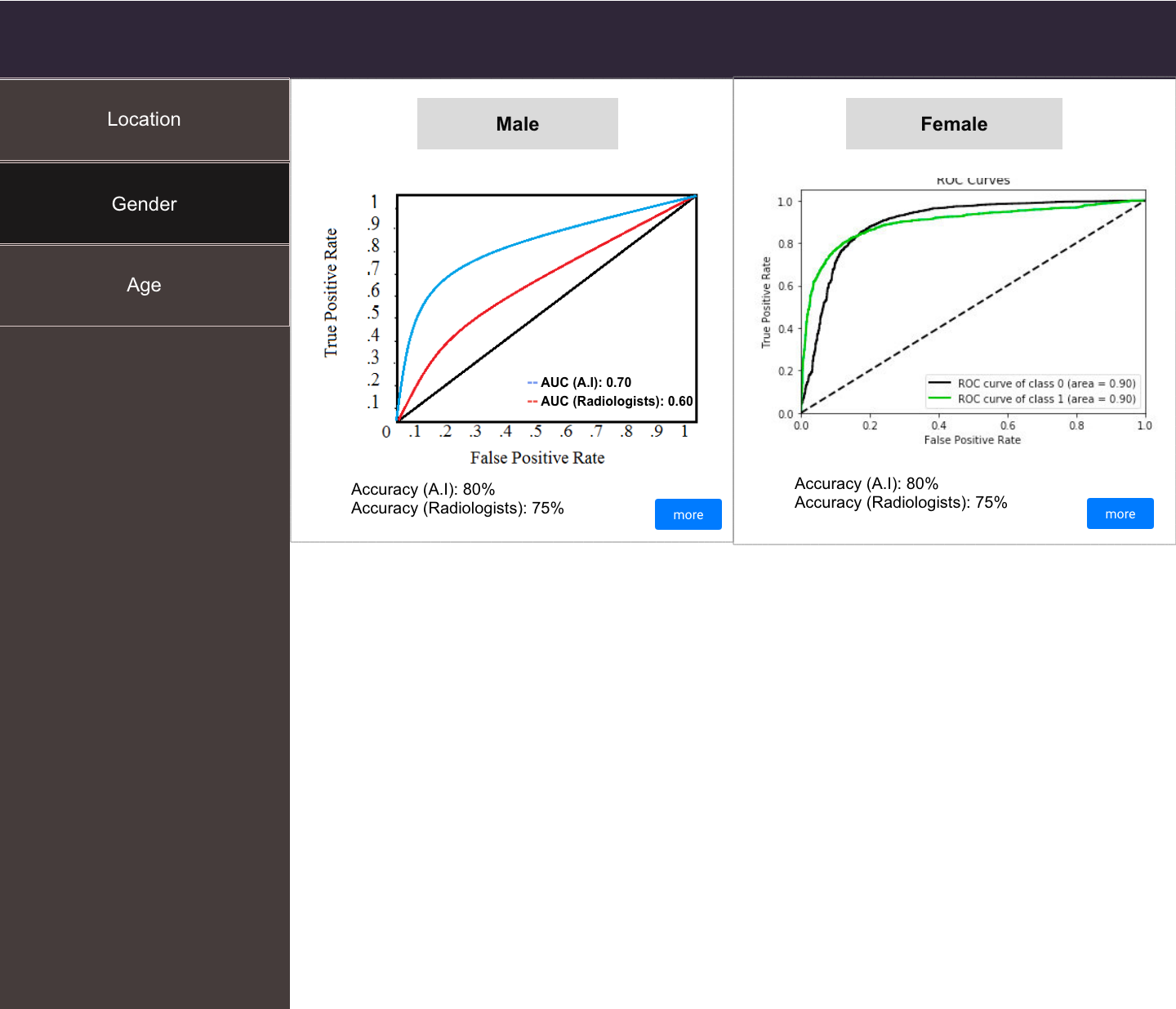
### Benchmark Categorizations

The evaluation results would be divided into Location, Gender and Age, as shown in Figure 1. Under Location, the performance of the AI model would be shown under the sub-categories; Country, Continent, Region and Global. The ‘Country’ sub-category shows the performance of the A.I system within the very nation it was developed. The ‘Continent’ sub-category would show how well the model performs on data from the continent it was developed in, this would help the developers know how well they can scale the current version of their A.I system. ‘Region’ specifically focuses on the performance of the AI system within the sub-continental region it was developed (e.g. West Africa, South East Asia, Northern Europe). This would help the developers see how ready their AI system is to be deployed in neighbouring countries. And finally, ‘Global’ shows how well the model performs on data from across the world, showing its ability to truly generalise. Each of the subcategories under location would also feature an AUC score for each Gender and Age group, as shown in Figure 1 and 3. This would allow developers to tell specifically within each geographical area, how well their AI system generalises across gender and age.

Under ‘Gender’, there would be two main sub-categories, Male and Female, as shown in Figure 1 and 4. This would show how well the AI system performs on radiographs of male and female patients. Each of the two sub-categories would also feature AUC scores for various Age groups. This would show how well the AI system performs on male and female patients of different age groups. Conditions that however only affect one gender would not feature the ‘Gender’ category.

The ‘Age’ category would feature various age groups as sub-categories. Age groups that are not featured within certain datasets and conditions would not be shown for those specific conditions. Similar to the other categories, an AI system’s performance on each of the age groups would be shown and it’d also feature ‘Male’ and ‘Female’ AUC score under each age group.

This concept of ‘Precision Evaluation’ is to precisely assess how well an AI system generalises across demographics.



**Figure 4: The ‘Gender’ category**

### Evaluation Data

The goal is to ensure proportional amount of the diverse demographics and their intersections. With diverse evaluation data, the generality of an AI system can truly be assessed. The platform would be open to facilities to register, and submit images and demographical data. Facilities with approved images would be credited with contributing to the set up of such dataset. This would hopefully serve as incentive to facilities to contribute more data to the platform. Submitted radiographs should be accompanied by a csv file with information about the patient's gender, age and imaging facility’s location. This would allow for the proposed Precision Evaluation framework.

### The Panel of Expert Radiologists

To ensure quality, submitted images and data would be reviewed by a panel of expert radiologists. This panel of expert radiologists would also ensure edge cases and diversity are represented in each evaluation set. The panel would be open to qualified radiologists to join and participate in. Each evaluation set and condition would have its own panel of expert radiologists. Radiologists who are part of the panel would be credited on the platform for the evaluation sets they contribute to. This would also hopefully serve as an incentive for more radiologists to join ‘The Panel of Expert Radiologists’.

### Test Radiologists

Beyond the panel of expert radiologists, we would ideally have radiologists from different parts of the world who would be asked to classify the test images without access to their true labels. The goal would be to get as many testing radiologists as possible from each continent, region or possibly country. These radiologists would also be ideally given test images from within their region. This would allow us to compare an A.I system’s performance on test images within each of the ‘Location’ sub-category with radiologists also within such geographical regions. This would more appropriately help us estimate how well an AI system performs when compared with the level of performance of standalone radiologists within each specific region.

## Evaluation Data Availability

minoHealth AI Labs is currently working with institutions in Ghana, including Christian Health Association of Ghana (CHAG), National Catholic Health Service (NCHS), Euracare Advanced Diagnostic Center and Paradise Diagnostic Center in order to collect mammograms and chest radiographs. Some of that data can be made available to the benchmarking platform. With the collaboration of various members and organisations affiliated with FG-AI4H, we can collect more radiographs from around the world. Also as explained earlier, the platform would be open to registered facilities to contribute data.

## Feasibility

Though the proposed radiograph-agnostic framework and platform has several moving parts and complexities, it’s possible to modularise it and build with different levels of complexities. It is also possible for the categories and subcategories to adjust based on the number and diversity of samples as well as radiologists available. If the evaluation data for a particular condition isn’t large enough to support all four subcategories of ‘Location’, it can be limited to just ‘Region’ or ‘Continent’ and ‘Global’. If there weren’t enough test radiologists within a specific country where an AI system was developed, the regional, continental or global average performance of radiologists would be used across. The same can apply to the sub-categories of Gender and Age. We would also start implementing the platform with chest x-rays for 12 different thoracic diseases supported in MIMIC-CXR, CheXpert and NIH Chest XRay datasets.

## Privacy and Security

Anonymised data can be de-anonymised using techniques like linkage attacks. Linkage attacks involve combining data from multiple sources in order to form a whole picture about targets. It is then possible to use the demographics data (Date of Birth, Gender and Location) of an anonymised patient whose medical image is available and cross-reference with public voter lists in order to identify who the patient is. This is because there are very few individuals likely to have the same data of birth and gender, and live in the same location. To prevent linkage attacks, the developers and testing radiologists are only given access to test images without demographics data. To further defend against this attack, we are abstracting ‘Date of Birth’ to just the Age (in years) of the patient when they were imaged, and we can abstract the location to just ‘Country’. To add additional security measures as far as the panel of expert radiologists has access to such demographics data, we can explore variations of Differential Privacy.

Also, we are ensuring a secure system by demanding that developers and organisations that require a standardised evaluation of their A.I systems register before they’d be allowed to. The registration process can include an in-person assessment by their local World Health Organisation (W.H.O) or ITU branch office, just to ensure they are a valid institution, startup or developer. A moderate fee can be charged for the registration, which could then serve as funds to support the maintenance of the platform. Equally, health facilities seeking to donate medical images and data must register and be assessed. And even the images and data they submit to the platform would be evaluated before being added to the system. All radiologists, both in the ‘panel of expert radiologists’ and the ‘testing radiologists’ would have to register and be verified before being allowed to contribute to the platform.

In order to not infringe upon the Intellectual Properties (IP) rights of AI developers and organisations, they would not be required to submit their A.I system itself. They are only supposed to submit the outputs (csv file) of their AI system, which would then be used for the evaluation of their system.

## Impact

There exists a large amount of publicly available medical image datasets online, and there have been a lot of research and development with such datasets. By developing frameworks that target these conditions first, we would make the standardized benchmarking platform immediately appealing to the A.I healthcare research and development community. This would also help speedup the deployment of AI solutions in Radiology globally. AI healthcare system developers and organisations usually have to go through the challenge of convincing health facilities to share their private data with them, such data unfortunately aren’t always of high quality and they usually lack the broad demographic representations needed to truly assess how well an A.I system generalises. A radiograph-agnostic benchmarking platform with data from various facilities across the globe, reviewed by a panel of experts to ensure quality and diversity, would drastically simplify the evaluation stage of such AI systems. The ‘Precision Evaluation’ framework would help fight against demographically biased A.I systems by ensuring they are tested in great detail across various groups. It’d also help in the safe scaling of AI systems across different locations. The ‘Location’ sub-categorization of evaluation allows for ‘Geo-Precision Evaluation’. Developers can tell how well their systems can perform within their country or first-point of deployment, and should they intend to scale to neighbouring countries then eventually have it across the globe, they can tell how well their current version would perform at each point of such growth and scaling.

## Reporting Methodology

* Report publication in papers or as part of ITU documents
* Online reporting
* public leaderboards vs. private leaderboards
* Credit-Check like on approved sharing with selected stakeholders
* Report structure including an example
* Frequency of benchmarking

# Results

* insert here the reports of the different benchmarking runs

# Discussion

* Discussion of the insights from executing the benchmarking on
* external feedback on the whole topic and its benchmarking
* technical architecture
* data acquisition
* benchmarking process
* benchmarking results
* field implementation success stories

# Declaration of Conflict of Interest

* by each contributor to this document

**References**

Andre Esteva, Brett Kuprel, Roberto A. Novoa, Justin Ko, Susan M. Swetter, Helen M. Blau & Sebastian Thrun (2017) Dermatologist-level classification of skin cancer with deep neural networks. Nature volume 542, pages 115–118

Arleo, Elizabeth & Hendrick, R. Edward & Helvie, Mark & Sickles, Edward. (2017). Comparison of recommendations for screening mammography using CISNET models. Cancer. 123. 10.1002/cncr.30842.

Bien N, Rajpurkar P, Ball RL, Irvin J, Park AK, Jones E, et al. AI-assisted diagnosis for knee MR: Development and retrospective validation. PLoS Med. 2018;15(11):e1002699. <https://doi.org/10.1371/journal.pmed.1002699>

CBIS-DDSM. <https://wiki.cancerimagingarchive.net/display/Public/CBIS-DDSM>

CheXpert. <https://stanfordmlgroup.github.io/competitions/chexpert/>. https://arxiv.org/abs/1901.07031

Clinical Radiology UK Workforce Census Report 2018 <https://www.rcr.ac.uk/publication/clinical-radiology-uk-workforce-census-report-2018>

H A Haenssle, C Fink, R Schneiderbauer, F Toberer, T Buhl, A Blum, A Kalloo, A Ben Hadj Hassen, L Thomas, A Enk, L Uhlmann, Reader study level-I and level-II Groups, Man against machine: diagnostic performance of a deep learning convolutional neural network for dermoscopic melanoma recognition in comparison to 58 dermatologists, Annals of Oncology, Volume 29, Issue 8, August 2018, Pages 1836–1842, https://doi.org/10.1093/annonc/mdy166

John R. Zech ,Marcus A. Badgeley ,Manway Liu,Anthony B. Costa,Joseph J. Titano,Eric Karl Oermann (2018) Variable generalization performance of a deep learning model to detect pneumonia in chest radiographs: A cross-sectional study. https://doi.org/10.1371/journal.pmed.1002683

MIMIC-CXR Dataset: <https://archive.physionet.org/physiobank/database/mimiccxr/>

<https://arxiv.org/abs/1901.07042>

NIH Chest XRay: <https://www.nih.gov/news-events/news-releases/nih-clinical-center-provides-one-largest-publicly-available-chest-x-ray-datasets-scientific-community>. [https://nihcc.app.box.com/v/ChestXray-NIHCC](https://nihcc.app.box.com/v/ChestXray-NIHCC/file/256057377774)

RAD-AID in Liberia. <https://www.rad-aid.org/countries/africa/liberia/>

Rajpurkar P, Irvin J, Ball RL, Zhu K, Yang B, Mehta H, et al. Deep learning for chest radiograph diagnosis: A retrospective comparison of CheXNeXt to practicing radiologists. PLoS Med. 2018;15(11):e1002686. https://doi.org/10.1371/journal.pmed.1002686

UCSF: Digital X-Ray On-The-Go in Kenya. <https://radiology.ucsf.edu/blog/digital-x-ray-go-kenya>

[1] WHO | World Health Organization n.d. https://www.who.int/diagnostic\_imaging/imaging\_modalities/dim\_plain-radiography/en/ (accessed August 1, 2020).

[2] X-rays | Radiology Reference Article | Radiopaedia.org n.d. https://radiopaedia.org/articles/x-rays-1?lang=us (accessed August 1, 2020).

[3] Conventional Radiography - Special Subjects - Merck Manuals Professional Edition n.d. https://www.merckmanuals.com/professional/special-subjects/principles-of-radiologic-imaging/conventional-radiography (accessed August 1, 2020).

[4] Arsalan M, Owais M, Mahmood T, Choi J, Park KR. Artificial Intelligence-Based Diagnosis of Cardiac and Related Diseases. Journal of Clinical Medicine 2020;9:871. https://doi.org/10.3390/jcm9030871.

[5] Hwang EJ, Park S, Jin KN, Kim JI, Choi SY, Lee JH, et al. Development and Validation of a Deep Learning-Based Automated Detection Algorithm for Major Thoracic Diseases on Chest Radiographs. JAMA Network Open 2019;2:e191095. https://doi.org/10.1001/jamanetworkopen.2019.1095.

[6] O S, M S, UJ M, DU J. An Efficient Deep Learning Approach to Pneumonia Classification in Healthcare. Journal of Healthcare Engineering 2019;2019. https://doi.org/10.1155/2019/4180949.

[7] Parveen NRS, Sathik MM. Detection of Pneumonia in chest X-ray images. Journal of X-Ray Science and Technology 2011;19:423–8. https://doi.org/10.3233/XST-2011-0304.

[8] Kermany DS, Goldbaum M, Cai W, Valentim CCS, Liang H, Baxter SL, et al. Identifying Medical Diagnoses and Treatable Diseases by Image-Based Deep Learning. Cell 2018;172:1122-1131.e9. https://doi.org/10.1016/j.cell.2018.02.010.

[9] Kitamura G, Deible C. Retraining an open-source pneumothorax detecting machine learning algorithm for improved performance to medical images. Clinical Imaging 2020;61:15–9. https://doi.org/10.1016/j.clinimag.2020.01.008.

[10] Filice RW, Stein A, Wu CC, Arteaga VA, Borstelmann S, Gaddikeri R, et al. Crowdsourcing pneumothorax annotations using machine learning annotations on the NIH chest X-ray dataset. Journal of Digital Imaging 2020;33:490–6. https://doi.org/10.1007/s10278-019-00299-9.

[11] Qin C, Yao D, Shi Y, Song Z. Computer-aided detection in chest radiography based on artificial intelligence: A survey. BioMedical Engineering Online 2018;17:113. https://doi.org/10.1186/s12938-018-0544-y.

[12] Kumar A, Wang YY, Liu KC, Tsai IC, Huang CC, Hung N. Distinguishing normal and pulmonary edema chest x-ray using Gabor filter and SVM. 2014 IEEE International Symposium on Bioelectronics and Bioinformatics, IEEE ISBB 2014, IEEE Computer Society; 2014. https://doi.org/10.1109/ISBB.2014.6820918.

[13] Mohd Noor N, Mohd Rijal O, Yunus A, Mahayiddin AA, Gan CP, Ong EL, et al. Texture-Based Statistical Detection and Discrimination of Some Respiratory Diseases Using Chest Radiograph. Lecture Notes in Bioengineering, Springer, Singapore; 2014, p. 75–97. https://doi.org/10.1007/978-981-4585-72-9\_4.

[14] Lee H, Tajmir S, Lee J, Zissen M, Yeshiwas BA, Alkasab TK, et al. Fully Automated Deep Learning System for Bone Age Assessment. Journal of Digital Imaging 2017;30:427–41. https://doi.org/10.1007/s10278-017-9955-8.

[15] Cicero M, Bilbily A, Colak E, Dowdell T, Gray B, Perampaladas K, et al. Training and Validating a Deep Convolutional Neural Network for Computer-Aided Detection and Classification of Abnormalities on Frontal Chest Radiographs. Investigative Radiology 2017;52:281–7. https://doi.org/10.1097/RLI.0000000000000341.

[16] Wang L, Lin ZQ, Wong A. COVID-Net: A Tailored Deep Convolutional Neural Network Design for Detection of COVID-19 Cases from Chest X-Ray Images. n.d.

[17] Apostolopoulos ID, Mpesiana TA. Covid-19: automatic detection from X-ray images utilizing transfer learning with convolutional neural networks 2020;43:635–40. https://doi.org/10.1007/s13246-020-00865-4.

[18] Narin A, Kaya C, Pamuk Z. Automatic Detection of Coronavirus Disease (COVID-19) Using X-ray Images and Deep Convolutional Neural Networks. n.d.

[19] Afshar P, Heidarian S, Naderkhani F, Oikonomou A, Plataniotis KN, Mohammadi A. COVID-CAPS: A Capsule Network-based Framework for Identification of COVID-19 cases from X-ray Images. n.d.

[20] Brunese L, Mercaldo F, Reginelli A, Santone A. Explainable Deep Learning for Pulmonary Disease and Coronavirus COVID-19 Detection from X-rays. Computer Methods and Programs in Biomedicine 2020;196:105608. https://doi.org/10.1016/j.cmpb.2020.105608.

[21] Ozturk T, Talo M, Yildirim EA, Baloglu UB, Yildirim O, Rajendra Acharya U. Automated detection of COVID-19 cases using deep neural networks with X-ray images. Computers in Biology and Medicine 2020;121:103792. https://doi.org/10.1016/j.compbiomed.2020.103792.

[22] Hwang EJ, Park CM. Clinical implementation of deep learning in thoracic radiology: Potential applications and challenges. Korean Journal of Radiology 2020;21:511–25. https://doi.org/10.3348/kjr.2019.0821.

[23] Zhu J, Shen B, Abbasi A, Hoshmand-Kochi M, Li H, Duong TQ. Deep transfer learning artificial intelligence accurately stages COVID-19 lung disease severity on portable chest radiographs. PLOS ONE 2020;15:e0236621. https://doi.org/10.1371/journal.pone.0236621.

[24] Matsumoto T, Kodera S, Shinohara H, Ieki H, Yamaguchi T, Higashikuni Y, et al. Diagnosing Heart Failure from Chest X-Ray Images Using Deep Learning. International Heart Journal 2020;61:781–6. https://doi.org/10.1536/ihj.19-714.

[25] Matsubara N, Teramoto A, Saito K, Fujita H. Bone suppression for chest X-ray image using a convolutional neural filter. Australasian Physical and Engineering Sciences in Medicine 2019. https://doi.org/10.1007/s13246-019-00822-w.

[26] Lee S, Choe EK, Kang HY, Yoon JW, Kim HS. The exploration of feature extraction and machine learning for predicting bone density from simple spine X-ray images in a Korean population. Skeletal Radiology 2020;49:613–8. https://doi.org/10.1007/s00256-019-03342-6.

[27] Hu TH, Wan L, Liu TA, Wang MW, Chen T, Wang YH. Advantages and Application Prospects of Deep Learning in Image Recognition and Bone Age Assessment. Journal of Forensic Medicine 2017;33. https://doi.org/10.3969/j.issn.1004-5619.2017.06.013.

[28] Li Q, Zhong L, Huang H, Liu H, Qin Y, Wang Y, et al. Auxiliary diagnosis of developmental dysplasia of the hip by automated detection of Sharp’s angle on standardized anteroposterior pelvic radiographs. Medicine (United States) 2019;98. https://doi.org/10.1097/MD.0000000000018500.

[29] Kitamura G. Deep learning evaluation of pelvic radiographs for position, hardware presence, and fracture detection. European Journal of Radiology 2020;130. https://doi.org/10.1016/j.ejrad.2020.109139.

[30] Zheng G, Nolte LP. Computer-aided orthopaedic surgery: State-of-the-art and future perspectives. Advances in Experimental Medicine and Biology, vol. 1093, Springer New York LLC; 2018, p. 1–20. https://doi.org/10.1007/978-981-13-1396-7\_1.

[31] Unberath M, Zaech JN, Gao C, Bier B, Goldmann F, Lee SC, et al. Enabling machine learning in X-ray-based procedures via realistic simulation of image formation. International Journal of Computer Assisted Radiology and Surgery 2019;14:1517–28. https://doi.org/10.1007/s11548-019-02011-2.

[32] Vaquero, J. J., & Kinahan, P. (2015). Positron Emission Tomography: Current Challenges and Opportunities for Technological Advances in Clinical and Preclinical Imaging Systems. Annual review of biomedical engineering, 17, 385–414. https://doi.org/10.1146/annurev-bioeng-071114-040723

[33] Mawlawi, O., Podoloff, D. A., Kohlmyer, S., Williams, J. J., Stearns, C. W., Culp, R. F., Macapinlac, H., & National Electrical Manufacturers Association (2004). Performance characteristics of a newly developed PET/CT scanner using NEMA standards in 2D and 3D modes. Journal of nuclear medicine : official publication, Society of Nuclear Medicine, 45(10), 1734–1742.

[34] Shiraishi, J., Li, Q., Appelbaum, D., & Doi, K. (2011, November). Computer-aided diagnosis and artificial intelligence in clinical imaging. In Seminars in nuclear medicine (Vol. 41, No. 6, pp. 449-462). WB Saunders.

[35] Imaging Modalities. (2016, December 02). Retrieved July 27, 2020, from https://www.who.int/diagnostic\_imaging/imaging\_modalities/en/

[36] Sia, M. (n.d.). Radiology basics - Imaging modalities. Retrieved July 27, 2020, from https://www.radiologycafe.com/medical-students/radiology-basics/imaging-modalities

[37] Fluoroscopy Procedure. (n.d.). Retrieved July 27, 2020, from https://www.hopkinsmedicine.org/health/treatment-tests-and-therapies/fluoroscopy-procedure

[38] Weese, J., Penney, G., Desmedt, P., Buzug, T., Hill, D., & Hawkes, D. (1997). Voxel-based 2-D/3-D registration of fluoroscopy images and CT scans for image-guided surgery. IEEE Transactions on Information Technology in Biomedicine, 1(4), 284-293. doi:10.1109/4233.681173

[39] Bang, J. Y., Hough, M., Hawes, R. H., & Varadarajulu, S. (2020). Use of Artificial Intelligence to Reduce Radiation Exposure at Fluoroscopy-Guided Endoscopic Procedures. The American Journal of Gastroenterology, 115(4), 555-561. doi:10.14309/ajg.0000000000000565

[40] "Review on the applications of ultrasonography in ... - NCBI." 28 Jan. 2016, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4731348/. Accessed 16 Sep. 2020

[41] "Ultrasound: Purpose, Procedure, and Preparation - Healthline." https://www.healthline.com/health/ultrasound. Accessed 16 Sep. 2020.

[42] "Ultrasound (Sonography) - RadiologyInfo.org." https://www.radiologyinfo.org/en/info.cfm?pg=genus. Accessed 16 Sep. 2020.

[43] "4 Types of Ultrasound Imaging • Ultrasound Technician." https://www.ultrasoundtechniciancenter.org/ultrasound-knowledge/medical-ultrasound-imaging-types.html. Accessed 17 Sep. 2020.

[44] "Deep Learning in Medical Ultrasound Analysis: A Review ...." https://www.sciencedirect.com/science/article/pii/S2095809918301887. Accessed 17 Sep. 2020.

[45] "Nuclear Medicine - WHO." https://www.who.int/diagnostic\_imaging/imaging\_modalities/dim\_nuclearmed/en/. Accessed 17 Sep. 2020.

[46] "Nuclear Medicine, General - RadiologyInfo.org." https://www.radiologyinfo.org/en/info.cfm?pg=gennuclear. Accessed 17 Sep. 2020.

[47] "Nuclear medicine - Wikipedia." https://en.wikipedia.org/wiki/Nuclear\_medicine. Accessed 17 Sep. 2020

[48] "Artificial intelligence and radiomics in nuclear medicine ...." 15 Nov. 2019, https://link.springer.com/article/10.1007/s00259-019-04593-0. Accessed 17 Sep. 2020

[49] "Mammography - Wikipedia." https://en.wikipedia.org/wiki/Mammography. Accessed 17 Sep. 2020.

[50] "Mammography (Mammogram) - RadiologyInfo.org." https://www.radiologyinfo.org/en/info.cfm?pg=mammo. Accessed 17 Sep. 2020.

[51] "Study: AI improves radiologists' readings of mammograms ...." 2 Mar. 2020, https://newsroom.uw.edu/news/study-ai-improves-radiologists-readings-mammograms. Accessed 17 Sep. 2020.

[52] "Magnetic Resonance Imaging (MRI)." https://www.nibib.nih.gov/science-education/science-topics/magnetic-resonance-imaging-mri. Accessed 18 Sep. 2020.

[53] "Magnetic resonance imaging - Wikipedia." https://en.wikipedia.org/wiki/Magnetic\_resonance\_imaging. Accessed 18 Sep. 2020.

[54] "Magnetic resonance imaging - WHO." https://www.who.int/diagnostic\_imaging/imaging\_modalities/dim\_magresimaging/en/. Accessed 18 Sep. 2020.

[55] "Artificial intelligence enhances MRI scans | National Institutes ...." 10 Apr. 2018, https://www.nih.gov/news-events/nih-research-matters/artificial-intelligence-enhances-mri-scans. Accessed 18 Sep. 2020.

[56] "Artificial intelligence in radiology - NCBI - NIH." https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6268174/. Accessed 18 Sep. 2020.

[57] "Angiography - WHO." https://www.who.int/diagnostic\_imaging/imaging\_modalities/dim\_angiography/en/. Accessed 18 Sep. 2020.

[58] "Angiography - Wikipedia." https://en.wikipedia.org/wiki/Angiography. Accessed 18 Sep. 2020.

[59] "Artificial intelligence in cardiovascular imaging: state of the art ...." 9 Aug. 2019, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6712136/. Accessed 18 Sep. 2020.

[60] Sharif, M. S., & Amira, A. (2009, November). An intelligent system for PET tumour detection and quantification. In 2009 16th IEEE International Conference on Image Processing (ICIP) (pp. 2625-2628). IEEE.

[61] Lakhan, S. E., Kaplan, A., Laird, C., & Leiter, Y. (2009). The interventionalism of medicine: interventional radiology, cardiology, and neuroradiology. International Archives of Medicine, 2(1), 27.

[62] Iezzi, R., Goldberg, S. N., Merlino, B., Posa, A., Valentini, V., & Manfredi, R. (2019). Artificial Intelligence in Interventional Radiology: A Literature Review and Future Perspectives. Journal of oncology, 2019.

[63] Abajian, A., Murali, N., Savic, L. J., Laage-Gaupp, F. M., Nezami, N., Duncan, J. S., ... & Chapiro, J. (2018). Predicting treatment response to intra-arterial therapies for hepatocellular carcinoma with the use of supervised machine learning—an artificial intelligence concept. Journal of Vascular and Interventional Radiology, 29(6), 850-857.

[64] Asadi, H., Dowling, R., Yan, B., & Mitchell, P. (2014). Machine learning for outcome prediction of acute ischemic stroke post intra-arterial therapy. PloS one, 9(2), e88225.

[65] Asadi, H., Kok, H. K., Looby, S., Brennan, P., O'Hare, A., & Thornton, J. (2016). Outcomes and complications after endovascular treatment of brain arteriovenous malformations: a prognostication attempt using artificial intelligence. World neurosurgery, 96, 562-569.

[66] Wachs, J. P., Stern, H. I., Edan, Y., Gillam, M., Handler, J., Feied, C., & Smith, M. (2008). A gesture-based tool for sterile browsing of radiology images. Journal of the American Medical Informatics Association, 15(3), 321-323.

[67] El‐Shallaly, G. E. H., Mohammed, B., Muhtaseb, M. S., Hamouda, A. H., & Nassar, A. H. M. (2005). Voice recognition interfaces (VRI) optimize the utilization of theatre staff and time during laparoscopic cholecystectomy. Minimally Invasive Therapy & Allied Technologies, 14(6), 369-371.

[68] Herniczek, S. K., Lasso, A., Ungi, T., & Fichtinger, G. (2014, March). Feasibility of a touch-free user interface for ultrasound snapshot-guided nephrostomy. In Medical Imaging 2014: Image-Guided Procedures, Robotic Interventions, and Modeling (Vol. 9036, p. 90362F). International Society for Optics and Photonics.

[69] Solbiati, M., Passera, K. M., Rotilio, A., Oliva, F., Marre, I., Goldberg, S. N., ... & Solbiati, L. (2018). Augmented reality for interventional oncology: proof-of-concept study of a novel high-end guidance system platform. European radiology experimental, 2(1), 18.

[70] Seals, K., Al-Hakim, R., Mulligan, P., Lehrman, E., Fidelman, N., Kolli, K., ... & Taylor, A. (2019). 03: 45 PM Abstract No. 38 The development of a machine learning smart speaker application for device sizing in interventional radiology. Journal of Vascular and Interventional Radiology, 30(3), S20.

[71] Letzen, B., Wang, C. J., & Chapiro, J. (2019). The Role of Artificial Intelligence in Interventional Oncology: A Primer. Journal of vascular and interventional radiology: JVIR, 30(1), 38.

[72] What is Computed Tomography? (2019, December 5). Retrieved September 19, 2020, from https://www.fda.gov/radiation-emitting-products/medical-x-ray-imaging/what-computed-tomography

[73] Scott C. Litin, M. (2020, March 11). Could CT scans cause cancer? Retrieved September 19, 2020, from https://www.mayoclinic.org/tests-procedures/ct-scan/expert-answers/ct-scans/faq-20057860

[74] Other Information Resources Related to Whole-Body CT Screening. (2019, June 14). Retrieved September 19, 2020, from https://www.fda.gov/radiation-emitting-products/medical-x-ray-imaging/other-information-resources-related-whole-body-ct-screening

[75] Ghanem, M. H. (1986). CT scan in psychiatry: A review of the literature. L'Encéphale: Revue de psychiatrie clinique biologique et thérapeutique.

[76] Li, W., Cui, H., Li, K., Fang, Y., & Li, S. (2020). Chest computed tomography in children with COVID-19 respiratory infection. Pediatric radiology, 1-4.

[77] Grillet, F., Behr, J., Calame, P., Aubry, S., & Delabrousse, E. (2020). Acute pulmonary embolism associated with COVID-19 pneumonia detected by pulmonary CT angiography. Radiology.

[78] Ahsan, M. M., Gupta, K. D., Islam, M. M., Sen, S., Rahman, M., & Hossain, M. S. (2020). Study of Different Deep Learning Approach with Explainable AI for Screening Patients with COVID-19 Symptoms: Using CT Scan and Chest X-ray Image Dataset. arXiv preprint arXiv:2007.12525.

[79] Zhao, J., Zhang, Y., He, X., & Xie, P. (2020). COVID-CT-Dataset: a CT scan dataset about COVID-19. arXiv preprint arXiv:2003.13865.

[80] Chassagnon, G., Vakalopoulou, M., Battistella, E., Christodoulidis, S., Hoang-Thi, T. N., Dangeard, S., ... & Hajj, S. E. (2020). AI-Driven CT-based quantification, staging and short-term outcome prediction of COVID-19 pneumonia. arXiv preprint arXiv:2004.12852.

[81] Zhang, K., Liu, X., Shen, J., Li, Z., Sang, Y., Wu, X., ... & Ye, L. (2020). Clinically applicable AI system for accurate diagnosis, quantitative measurements, and prognosis of covid-19 pneumonia using computed tomography. Cell.

[82] Venugopal, V. K., Vaidhya, K., Murugavel, M., Chunduru, A., Mahajan, V., Vaidya, S., ... & Mahajan, H. (2020). Unboxing AI-Radiological Insights Into a Deep Neural Network for Lung Nodule Characterization. Academic Radiology, 27(1), 88-95.

[83] Seifert, R., Weber, M., Kocakavuk, E., Rischpler, C., & Kersting, D. (2020, September). AI and Machine Learning in Nuclear Medicine: Future Perspectives. In Seminars in Nuclear Medicine. WB Saunders.

[84] Gallo, M., Spigolon, L., Bejko, J., Gerosa, G., & Bottio, T. (2020). How to evaluate the outflow tract of LVAD after minimally invasive implantation by 3D CT‐scan. Artificial Organs.

[85] Le, V., Frye, S., Botkin, C., Christopher, K., Gulaka, P., Sterkel, B., ... & Osman, M. (2020). Effect of PET Scan with Count Reduction Using AI-Based Processing Techniques on Image Quality. Journal of Nuclear Medicine, 61(supplement 1), 3095-3095.

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