Enhancing diagnostic quality and productivity with AI

How machine intelligence is assisting clinicians

Executive summary

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Artificial intelligence (AI) is being introduced into healthcare through clinical imaging analysis and embedded in algorithms inside medical devices. Whether diagnostician, radiologist, or oncologist, a significant part of the life of a physician is spent examining images and writing reports about them; therefore, currently the bulk of commercial activity in AI in healthcare is in imaging analysis. There is a huge opportunity to augment physicians with AI-based systems that can reduce the workload across protocoling, imaging analysis, and automated reporting of the results.

Currently AI in reporting systems represents about 20% of the AI activity, helping to populate initial reports with statistics and measurements, and make predictions about the patient's recovery. Some 80% of AI activity in clinical imaging is on image analysis.

The patients journey in a sense starts with the ordering process, which then takes them to an imaging center or inpatient scanner. Protocoling is a big portion of the time consumption for a radiologist, since ordering-providers are often in doubt about what kind of protocol should be used to examine a specific condition. Protocoling could be a potential target for AI systems. Report generation and quantification (measurements) also represent significant portions in terms of radiologists' time. Lesion detection AI algorithms are helpful in improving quality and sensitivity of a radiological exam, and lesion characterization may improve specificity (the true negative rate).

Currently much of AI related activity is focused in searching for lesions in images, a time-consuming activity that is overwhelming radiologists as the number of images generated per patient scan is increasing at a faster rate than the growth in available radiologists. Patients are waiting many days to be seen by a physician: e.g. one radiologist for every 10k in the US, 1 in 100k in India, there is a backlog of 23k chest x-rays in the UK - all of this at an error rate of 5% by conservative estimates (statistics presented at Nvidia GTC). There is a high potential for AI systems to assist radiologists going through these backlogs, assisting physicians to be more productive and help improve accuracy.

The major scanner manufacturers, including GE Healthcare, Esaote, Philips Healthcare, and Siemens Healthcare in North America and Europe, and based in East Asia Fujifilm, Shimadzu, and Toshiba, all use NVIDIA GPUs for visualization, helping accelerate scanned images by processing the magnetic resonance signals, ultrasound, or x-ray data streams. This has made it easier to bring AI algorithms such as deep neural networks into scanning instruments, which typically already have GPUs installed for the advanced graphics rendering. AI systems require hardware acceleration to run in a reasonable amount of time, and GPUs have found a serendipitous role in performing such acceleration.

Deep learning, a recent neural network architecture that is highly successful in image analysis, is used for image reconstruction, acquisition, and protocoling, making the machines run faster, with higher quality images, and higher cost savings. For example, Matthew S. Rosen and team at Athinoula A. Martinos Center for Biomedical Imaging have trained AI systems by adding noise to the inputs for images with identified and labeled lesions (see "Image reconstruction by domain transform manifold learning", arXiv:1704.08841). The result is that the AI system can produce high quality images even with noisy inputs, making the scanner immune to noise.

This report delves into many advances in clinical imaging being introduced through AI. The activity today is mostly focused on working with the current computational environment that exists in the radiologist's laboratory, and examines how advanced medical instruments and software solutions that incorporate AI can augment a radiologist’s work. The end goal could be an integrated system that replaces much of the legacy equipment and assists in: performing scans, analyzing images, and producing reports through one connected solution. Throughout the patient’s journey and the radiology workflow we envisage the skilled radiologist as always present. The focus is on the radiologist plus AI, and not on replacing the radiologist, as hype and/or fear about AI tended to imply. AI can reduce the burden on radiologists, provide more time for high value work that results in quality improvement and lowers costs.

Key messages

- Machine intelligence is not replacing but assisting medical experts: AI plus physician is better than physician or AI alone.
- AI can deliver medical imaging experts significant productivity gains.
- The AI systems do not need to achieve perfection to be useful, as variability exists among the best radiologists, rather the AI system should produce results akin to the top percentiles of radiologists’ performance.
- The opportunity with AI is to devise systems that improve patient outcomes, and use all available data to improve diagnostics, not just image scans but medical records, clinician notes, and other unstructured data.
- At this stage of the introduction of AI systems in medical practice, it is easier to use AI for quantification and satisfy FDA Class II regulation than the more stringent FDA Class III that would be needed to use AI for interpretation purposes.

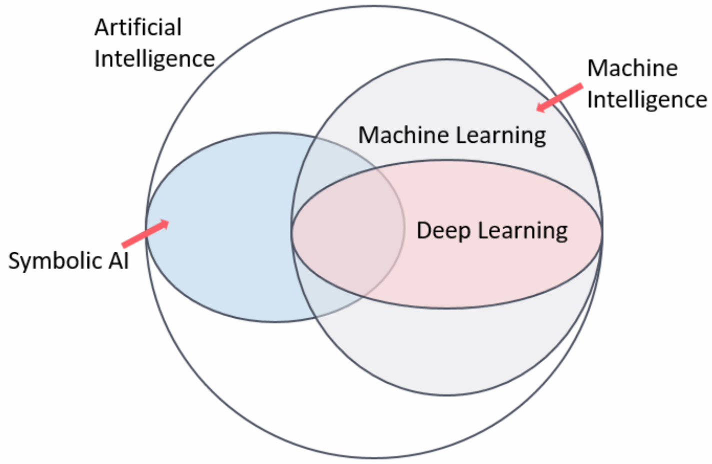
Introduction: why radiologist plus AI

In healthcare, imaging modalities include optical, magnetic resonance imaging (MRI), x-rays, computed tomography (CT), positron emission tomography (PET), and ultrasound, with imaging applied to whole body, specific body locations, or samples. Just one scan alone can generate upwards of 3000 images. The number of computed tomography (CT) scans in use today (the imaging workhorse in clinics) has approximately grown by from 29% to 50% and continues to grow. The growth in number of trained radiologists is only 5% – this represents a widespread bottleneck in processing images.

Image analysis and diagnosis is therefore an ideal candidate task for intelligent automation to help radiologists manage this increasing workload. With the recent advances in artificial intelligence (AI) there is an opportunity to bring intelligent automation into the clinic today, and this explains the surge of investment in startups, as well as activity among the leading image equipment suppliers.

AI is a broad research activity that ultimately aims to replicate the human (‘wetware’) brain’s intelligence in an artificial (e.g. computer) form; parity with humans is described as artificial general intelligence, capabilities that are close to but below human capabilities Ovum describes as artificial narrow intelligence, and our current state-of-the-art Ovum describes as machine intelligence – see Figure 1. Machine intelligence (MI) is mostly concerned with solving specific problems using methods inspired by the brain but not necessarily attempting to emulate the brain. Deep neural networks, an MI architecture), can employ networks with many layers (e.g. 150 layers) and contain many thousands of neurons. The overall architecture can combine different types of neural networks, such as convolutional neural networks and recurrent neural networks.

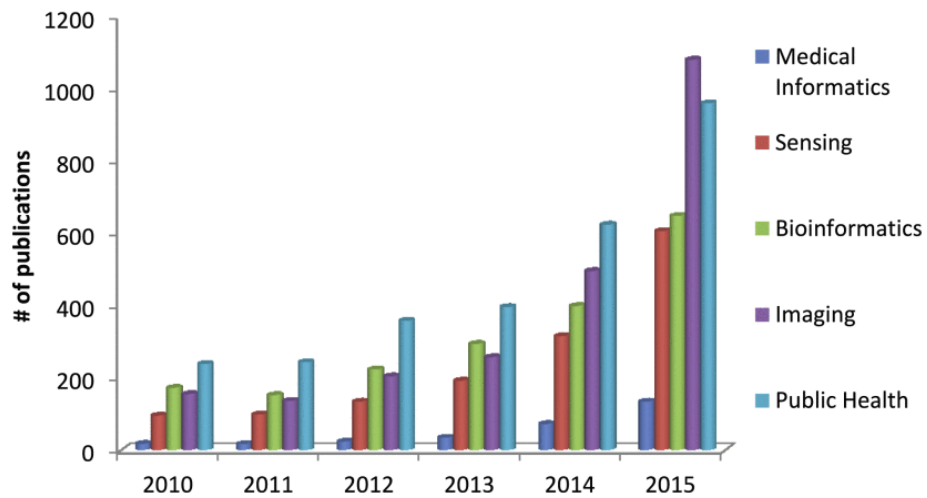
Figure 1: AI and its branches



Source: Ovum

In examining how radiologists spend most of their time, it is found that the bulk (as much as 80%) is not spent in the highest value work—such as expert analysis, impression, recommendations—but in the necessary chore of measuring, segmenting, organizing and reporting findings while going through each image, one at a time. This also impacts the radiologist's sensitivity and specificity metrics. The pressure on radiologists is so high given the high data workload that many complain there is not enough time to adequately inspect every image. This problem is being raised as an important quality and safety issue in healthcare.

Figure 2: Distribution of published papers that use deep learning in subareas of health informatics. Publication statistics are obtained from Google Scholar; the search phrase is defined as the subfield name with the exact phrase deep learning and at least one of medical or health appearing, e.g., "public health" "deep learning" medical OR health



Source: Daniele Ravi et al, Deep Learning for Health Informatics, IEEE Jrnl. for Biomedical and Health Informatics, vol. 21, pp.4-21, January 2017.

Moreover, AI systems are not able to replace the highly-skilled radiologist since these systems currently rely on heavily on large amounts of validated data, supervised learning and specificity of the task at hand. The radiologist's role in the healthcare system is relatively broad including: consultation on appropriate imaging modality, protocols, safety determinations, image-guided procedures, identification of findings in various organ systems and generating a diagnostic impression with patient specific recommendations. The AI systems are best utilized to augment the radiologist's activities. Taking on the time consuming and repetitive task of searching and labeling lesions is ideal for automation. In addition, AI systems may be useful in assisting diagnosis by characterization, and hence the search and diagnosis tasks are being targeted for AI systems in a supporting role. With the shortage of skilled radiologists across the globe being able to automate time-consuming activities, frees up the experts to focus on higher value tasks and reduces the pressure on the manpower.

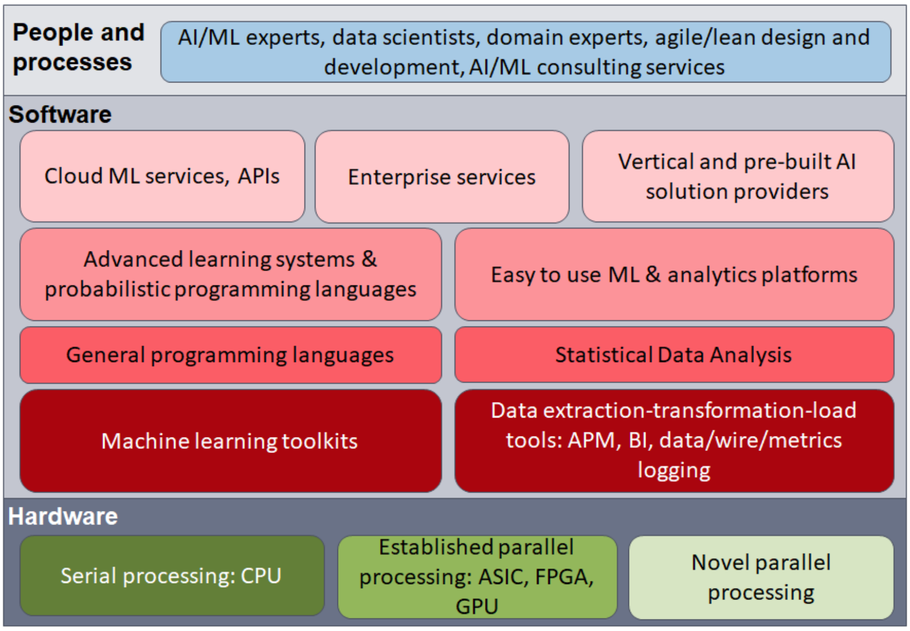
The published research on deep learning in healthcare has surged in the last few years – see Figure 2. Deep learning being applied to imaging shows the highest growth. The field of AI in medicine is at the brink of transforming healthcare, this report highlights the key activities across research and in the commercial sector.

The rise of machine intelligence and its role in healthcare

AI and its subset of machine intelligence (MI) have made huge progress in recent years, especially with deep learning neural networks, which are able to outperform humans in well-defined tasks, such as image recognition and image discrimination.

The MI technology stack is shown in Figure 3. A key layer is the hardware for AI acceleration. It is only practical to train an MI system and then run it in production—called inference mode—with the assistance of accelerators, a CPU alone is insufficient. Use of GPUs is critical in creating AI systems that can be trained quickly and produce results in near real-time. The software layer is where the AI system is constructed and trained. For radiologists, there are turnkey imaging analysis solutions available that remove the burden of building an AI system from scratch. This market has expanded considerably in the last two years.

Figure 3: Machine intelligence technology stack



Source: Ovum

Finally, the top layer represents the skilled personnel required to create and run the AI system. With turnkey solutions the emphasis is on ease of use by radiologists who are not expected to be experts in MI. The integration of AI systems with existing equipment found in radiology labs is a consistent theme of the vendors in this space, for example connecting to a picture archiving and communication system (PACS), as well as reporting tools.

The tasks in object detection in image analysis can be summarized, in increasing complexity, as follows:

- **Classification**: identifying the nature of a distinct object.
- **Detection**: identifying location of distinct objects: using classification of multiple objects.
- **Segmentation**: drawing a boundary around distinct objects, separating them out.

These same tasks have similar goals in medical imaging:

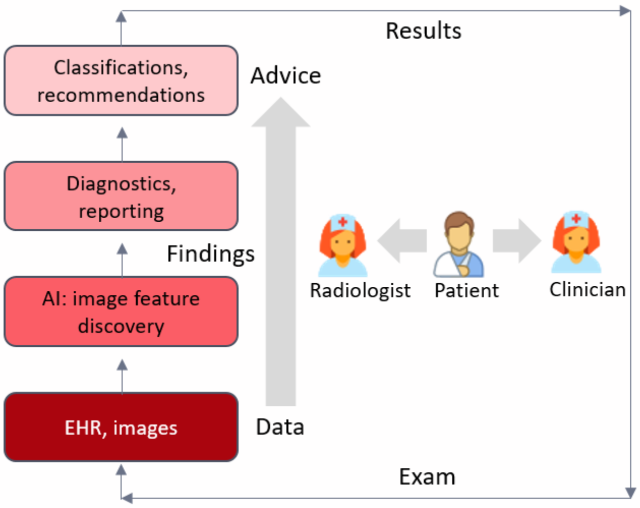
- **Detection**: are there lesion(s) and where are they?
- **Segmentation**: drawing an outline around lesion(s).
- **Classification**: what is the diagnosis?

AI using deep neural networks has proven to be superior to an individual operator in image classification, detection, and segmentation, and this has driven the surge in AI startups, with healthcare being one of the most active areas. AI in healthcare can be seen as a way of “combining” the knowledge of multiple experts in the field in a single piece of software.

Benefits of AI applied to imaging

Medical imaging applications are multi-fold, for example radiology, oncology, urology, ophthalmology, pathology, mammography, dermatology, and hematology. The number of images collected is rising exponentially and this accumulating mountain of images is posing a challenge for the healthcare sector as they try to keep pace with the demand for analysis. There is also an expanding range of data now available for analysis. Electronic, medical records make it easier to collect information on patients—from structured data contained in current and historical image scans, data from implant devices, to unstructured data in forms, reports, examination notes, patient history, admission/discharge/transfer information., Going forward, the prospect of patients uploading their own images and data using smart phones and other devices will further add to the volume of data available. There is no one integrated and standardized system in the healthcare sector—one hospital can use one system, a primary care physician another, a specialist another system, etc. This disparity makes sharing information for a collective/comprehensive view of the patient very difficult. However, this data deluge challenge is also an opportunity for improved diagnosis if the data can be managed and processed.

Figure 4: The role of AI in the patient lifecycle



Source: Ovum, based on Prof. Keith Dreyer, icons copyright Icons8

This is where AI can help. AI can mine the whole range of structured and unstructured data across disparate repositories to provide a more comprehensive analysis of an individual patient. Figure 4 shows the patient lifecycle and where AI can help, assisting radiologists in finding interesting features. A further thought is that many clinical tests have been devised and selected based on how easy it is for humans to interpret the results; but pointed out by Keith Dreyer (associate professor at Harvard Medical School, and Vice Chairman of Radiology and Chief Data Science Officer for the Departments of Radiology at Mass General Hospital and Brigham Women's Hospital), is that tests should also be considered based on usefulness for an AI system.

Another question relates to the differences among radiologists in how they interpret images and arrive at a diagnosis, and how accurate the AI system needs to be, to be useful. Different radiologists will vary in their receiver operating characteristics or ROC curve, which plots sensitivity against specificity. Additionally, looking at the overall ability of radiologists to interpret results as plotted on a bell curve Dreyer points out that an AI system will be useful if it sits to the right of the bell curve peak, and not necessarily be a perfect classifier. This is relevant in two respects. Labeling of data is performed by humans, so the variability in how humans label the data affects what the machine learns. And secondly, attempting to achieve a 'perfect' score in a machine learning system may be unattainable whereas achieving a capability score that is at least as good as the best humans may be attainable and useful.

In terms of where the AI element should be placed in the patient lifecycle, according to Charles Kahn's Radiology Gamuts Ontology, there are 2,613 different findings and 23,373 conditions in organ systems in the human body. AI can be best used for quantification of these findings as this requires satisfying the lesser FDA Class II (510K) regulation, whereas AI applied to interpretation would require passing the stringent FDA III (premarket approval) regulation.

One aspect being explored is to assist radiologists in protocoling: the controls of a modern scanning machine can resemble a 747 cockpit, with a multitude of knobs that need to be set. If the controls are sub-optimally set then the images will be sub-optimal, the resultant image will be sub-optimal, and this can make the diagnosis more difficult. An example of the state-of-the-art today in assisting radiologists with this challenge is from GE Healthcare, whose ultrasound system for cardiac imaging has embedded AI within the machine. These scans take a long time to position the instrument at the right point, and once there the radiologist must bring up the relevant machine menu for that area of the body. AI helps by predicting what type of image is being sought and automatically configures the machine for the optimal image setting. Additionally, GE Healthcare and Partners HealthCare have recently embarked on a ten-year long partnering initiative with the goal of integrating AI throughout every part of the patient experience—this underscores the growing recognition and importance of AI within the healthcare arena. Initial focus for the collaboration is on creating deep learning tools to enhance diagnostic imaging, from monitoring tumor growth to determining the likelihood of cancer from ultrasound scans.

Another commercial offering is from Butterfly Networks which has a camera on a handheld probe and uses AI to tell the user where to move the probe to acquire the right images. Butterfly Networks was recently FDA cleared in the USA for 13 applications and provides whole body imaging for under $2k.

Population health is another aspect of AI in healthcare being explored. Patients have scans taken throughout their life for multiple reasons and this represents a valuable data set that can be mined for early detection of disease. This may be particularly valuable for fighting the largest cancer mortality, lung cancer, which is not the most screened cancer. The problem with lung cancer is that it can take years before symptoms appear by which point the cancer has metastasized. However, detecting lung cancer early reduces mortality as it can be successfully treated, and so screening all a patient's available images using AI is an opportunity to detect disease onset.

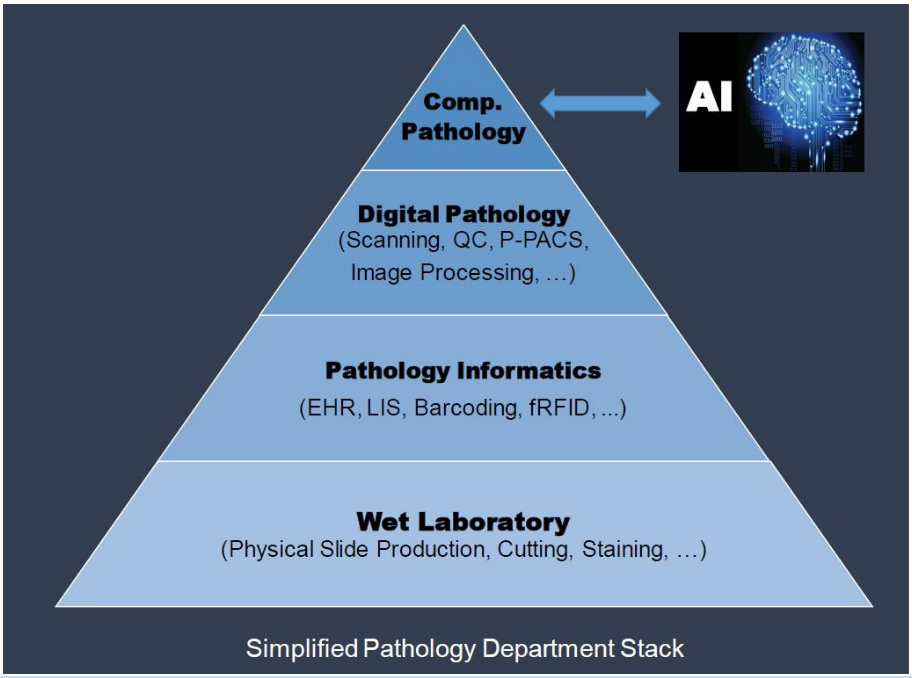
Zebra Medical is one AI startup looking at population health and has recently signed up with Google in this venture. Another is Lunit, which aims to detect tuberculosis among the population, especially in third world countries by taking its service in a truck to remote villages. Traditionally, if a team finds a patient with a potential ailment they obtain a sample which then must be taken back to hospital for analysis and then, if found positive, revisit the patient for treatment. The Lunit system allows on the spot analysis and treatment.

AI is leading to what is termed the intelligent hospital, assisting with workflow and patient assessment. For example, unless there is a known urgency, the imaging data typically goes into a single 'first in-first out' queue, with wait times that can vary from 10 min to multiple hours. By using AI in triage, if the system identifies an urgent case, such as high risk of a stroke, then it can move the patient to the top of the queue. This has a significant effect in reducing mortality, as the few urgent cases get seen quickly, and the change in queue has minimal effect on the other patients.

Image classification has been a great success for deep learning algorithms, however the ImageNet competitions popular for comparing deep learning algorithms used 469x387 pixel sizes (with some variation), and typically cropped to 256x256 pixels, whereas a typical CT scan will have resolution of 512x512x300 pixels, or in computational pathology 100k x 60k x 474 slides. Processing higher resolution images will require more powerful AI accelerators. We see for example NVIDIA releasing ever more powerful GPUs tailored toward these applications and we can see how this improvement in computation will be beneficial for furthering progress in this realm.

To improve AI diagnosis accuracy, there is an abundance of additional data that can be used by the AI system: scan and patient data (demographics, referral letter, past scans and reports, and scanner meta-data). Combined these broader data sets lead to better models than just feeding image data to the AI models. The comparison of scanned images, i.e. use of prior images, is one of the most powerful methods for detecting growth of cancers.

Figure 5: Simplified pathology department stack



Source: Thomas J Fuchs, co-founder of Paige.ai, presented at NVIDIA GTC 2017.

Radiology and genomics both assist in pathology and AI assisted computational pathology brings another level of capability by combining quantitative analysis of pathology, radiology and genomics – see Figure 5. This research is at an early stage but already startups are investigating the field, e.g. Paige.ai.

High-content screening microscopy is another opportunity for deep learning based image analysis. Applications include image based drug profiling for use in drug discovery, and functional genomics, to understand the function of every gene that is being imaged. AI is being used in phenotypic profiling which involves single cell segmentation, feature extraction and selection, clustering and visualization, and classification (see work by Thomas J Fuchs, co-founder of Paige.ai).

There is also a role for AI-based assistance in eliminating a broad range of errors in healthcare. According to an Institute of Medicine study and a New York study (American Hospital Association, Hospital Statistics, Chicago, 1999), there were between 44,000 and 98,000 deaths due to medical errors in 1997 in the USA, and other nations have similar statistics relative to the number of admissions. Therefore, there is scope for AI assisted healthcare beyond medical imaging; according to Dr Michael Dahlweid, Chief Medical Officer Digital at GE Healthcare, this includes multi-modal clinical decision support, healthcare assets and predictive optimization—an example being vetting documents for incorrect or inconsistent information.

Finally, looking further ahead to the possibilities of how AI can be introduced in the patient lifecycle, there is the complication that significant variables affect each patient. First, patients vary greatly in the genomic and molecular aspects of their disease. Secondly, there is also phenotypic diversity with variable appearances of disease in patients and of lesions in images. Finally, there is clinical diversity where patients have different responses to treatment. Given such individual variability it is being conceived that the way forward is personalized healthcare, also called precision medicine, where the individual is given unique treatment. Some medical researchers are proposing that AI is the step that will make such individual treatment possible at scale.

Market overview in AI imaging analysis and diagnostics

Across established medical technology vendors there is growing interest in use of AI, including the market leading scanner manufacturers. IBM recently purchased Merge Healthcare for $1 billion to enter this sector, and is using it with IBM Watson to bring AI into products, working with third-party suppliers in healthcare, such as Agfa, Philips, and Siemens.

While total investment on AI in this sector is small compared with investment in say, precision medicine, it is on a growth curve. The funding of AI startups in the medical imaging space is estimated at over $100 million, with the largest of these being Israel-based Zebra Medical Vision, receiving a total of $20m, and Enlitic not far behind at $15m. The Appendix tabulates the AI startups active in imaging at time of writing.

NVIDIA’s role in AI and healthcare

NVIDIA GPUs already power AI algorithms, making it possible to run the advanced imaging solutions examined in this report in near real-time. NVIDIA graphic processing units (GPUs) have moved beyond this capability into massively parallel computing, where GPUs can process signal and imaging algorithms at speeds that previously required many racks of traditional data center CPUs, enabling the computational acceleration that has been the foundation of the success for deep learning systems. This computational acceleration has reduced training time of deep neural networks from months to days or hours and running the AI systems in production (inference mode) in near real-time.

NVIDIA is also supporting the development of software frameworks and environments for developing solutions on GPUs. The NVIDIA CUDA library is the interface for writing the highest performance parallel computing applications. To support AI, NVIDIA offers an interactive environment, the Deep Learning GPU training system (DIGITS), which is freely available to help train engineers, data scientists, and other professional get to speed in developing AI systems, without requiring programming skills. DIGITS manages data, helps design and train neural networks on multi-GPU systems, monitors performance in real time with advanced visualizations, and selects the best performing model from the results for deployment. DIGITS supports the latest deep learning toolkits, including the current favorite, TensorFlow.

NVIDIA has been active in the medical imaging and intelligent machine design field for the last 10 years, and its GPUs are present in most of the scanners used world-wide. The latest Volta GPU embeds a supercomputer in these instruments, able perform 320 trillion operations per second. Specifically, the GPU contribution in the past 10 years in healthcare by NVIDIA was to lead the shift from the old, filtered back-projection reconstruction imaging method, to an iterative reconstruction method, which significantly reduced radiation doses worldwide and for example, prevented thousands of cases of leukemia in the pediatric population (an unfortunate side effect of radiology mitigated).

The addition of AI systems can be undertaken easily with the computation capability already present. Many hospital research labs, universities, and scanner manufacturers are building next generation AI-powered diagnostic machines.

NVIDIA and healthcare technology specialist Nuance have formed a partnership to bring machine learning to radiologists and data scientists working across the entire healthcare system. Nuance’s

PowerScribe radiology reporting and PowerShare image exchange network combined with NVIDIA's deep learning platform offer an end-to-end methodology for development and deployment of imaging AI models into the existing workflow of thousands of radiologists, helping them quickly detect key clinical findings and improve patient care.

NVIDIA is also growing an eco-system around using its technology in various vertical applications, including in healthcare, through its Deep Learning Institute. Thousands of people go through courses at the institute, where some 50% of use cases are based on healthcare topics. The hands-on labs involve carefully selected problems that NVIDIA has put together. NVIDIA also has a team of PhDs in medical imaging that it can bring into any problem, with a scaled engagement possible for clients, running workshops and being more closely involved in client activities.

Appendix

AI startup market in medical imaging

The following table lists a range of AI startups in medical imaging, by specialization, image diagnostics being the largest group. The large number of players is an indication of the investment flowing into this sector.

Figure 6: AI startups in medical imaging

Breast imaging	Cardiovascular imaging	Handheld scanner	Image diagnostics	Lung imaging	Neurological imaging
ClearView Diagnostics CureMetrix Densitas Quantitative Insights QView Medical ScreenPoint Medical VisExcell Volpara Solutions	Arterys Baylabs DiA Imaging Analysis	Butterfly Network	4Quant Aidence behold.ai Blackford Analysis Contextflow DeepCare Deep Genomics Enlitic Entopsis Image Analysis Group (IAG) imagia Imagen Technologies Lunit MD.ai Predible Health Quibim S.L. qure.ai Zebra Medical Vision	DiaScan HealthMyne Imbio RadLogics	Avalon AI combinostics icometrix MedyMatch

Source: Ovum

Further Reading

2018 Trends to Watch: Machine Intelligence, Ovum IT0014-003350 (October 2017).

Machine intelligence technology stack: what you need to build AI systems, Ovum IT0014-003330, (September 2017).

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