Evaluation of deep convolutional neural networks for automatic classification of common maternal fetal ultrasound planes

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The goal of this study was to evaluate the maturity of current Deep Learning classification techniques for their application in a real maternal-fetal clinical environment. A large dataset of routinely acquired maternal-fetal screening ultrasound images (which will be made publicly available) was collected from two different hospitals by several operators and ultrasound machines. All images were manually labeled by an expert maternal fetal clinician. Images were divided into 6 classes: four of the most widely used fetal anatomical planes (Abdomen, Brain, Femur and Thorax), the mother’s cervix (widely used for prematurity screening) and a general category to include any other less common image plane. Fetal brain images were further categorized into the 3 most common fetal brain planes (Trans-thalamic, Trans-cerebellum, Trans-ventricular) to judge fine grain categorization performance. The final dataset is comprised of over 12,400 images from 1,792 patients, making it the largest ultrasound dataset to date. We then evaluated a wide variety of state-of-the-art deep Convolutional Neural Networks on this dataset and analyzed results in depth, comparing the computational models to research technicians, which are the ones currently performing the task daily. Results indicate for the first time that computational models have similar performance compared to humans when classifying common planes in human fetal examination. However, the dataset leaves the door open on future research to further improve results, especially on fine-grained plane categorization.

Ultrasound (US) examination is an essential tool to monitor fetus and mother along pregnancy, providing an economic and non-invasive way to observe the development of all fetal organs and maternal structures. Several measures obtained from maternal-fetal scans are commonly used to monitor fetal growth1. The most commonly used biomarkers in clinical practice for the screening of fetal abnormalities are fetal biometries, estimates of fetal weight, and/or Doppler blood flow2. For example, muchal translucency measurement is the basis for the first trimester screening of fetal aneuploidies3, estimated fetal weight is used to detect abnormal growth4, fetal lungs can be used to predict neonatal respiratory morbidity5 and uterine cervix can be used to determine the risk of a preterm delivery6,7.

The acquisition of fetal and maternal ultrasound images in most fetal medicine centers is done following international guidelines promoted by scientific committees8,9. This means that images are obtained following the same protocols in a repeatable way. Indeed, images need to be acquired in a specific plane to be useful for diagnosis, to decrease the inter- and intra-observer variability and to allow the measurement of specific structures. Typically, more than 20 images are acquired for each ultrasound examination within mid-trimester screening ultrasound10. Occasionally, three dimensional (3D) images and videos can also be acquired to complete the clinical examination.

Both in a clinical setting and in research projects, a fetal specialist reviews the sonographer’s examinations, selecting images containing the structures of interest. Usually, trained research technicians, followed by a validation from a senior maternal-fetal expert, manually perform this task. However, since each screening ultrasound...
Artificial Intelligence has undergone impressive growth during the last decade, in particular with the emergence of Deep Learning (DL)\(^\text{10}\) and its remarkable progress in image recognition tasks via Convolutional Neural Networks (CNNs). In the last few years, CNNs have shown their usefulness in a wide set of medical applications, such as dermatology\(^\text{11}\), radiology\(^\text{12}\) and/or to classify or segment organs and lesions in images from computer tomographies and MRI\(^\text{13}\). These methods are known to excel “at automatically recognizing complex patterns in image data and provide a quantitative, rather than qualitative assessment”\(^\text{14}\).

However, in comparison, the use of CNNs in US remains limited to date\(^\text{15}\). And even more so prior work at using CNNs to select or classify US planes. The majority of this work detects US planes of interest from 2D\(^\text{14,15}\) or 3D\(^\text{16,17}\) video data. For example\(^\text{14}\), was the first to use CNNs for real-time automated detection of 13 fetal standard scan planes, the method uses weak supervision based on image level labels. The study used very rich data, with carefully acquired videos longer than the usual ones acquired in clinical practice. Each US video was approximately 30 minutes long, which provided surrounding and additional information to the CNNs. In\(^\text{15}\), authors used conditional random field models to detect the fetal heart in each frame of the 2D video. Video data information was used to take into account the temporal relationship between the frames\(^\text{16}\): proposed an hybrid method, which uses Random Forests to localize the whole fetus in the sagittal plane and, then CNNs to localize the fetal head, fetal body and non-fetal regions (in axial plane images). To obtain the best fetal head and abdomen planes the method uses clinical knowledge of the position of the fetal biometry planes within the head and body. Finally\(^\text{17}\), proposed an iterative approach with multiple passes of CNN to detect standard planes in 3D fetal brain US.

Although ultrasound studies are a real-time evaluation with recognition of the planes and structures from real-time moving images, currently, relying in video or 3D data limits its use for retrospective studies, since videos and/or 3D US are not always performed or saved. The majority of data stored in fetal clinics are 2d still images, for several reasons such as including standard planes for systematic measurement of fetal anatomy, recording a representive view of a real-time evaluation of fetal anatomy to demonstrate that this has been assessed as normal, and the existing cost of storage of large volumes of data in PACS systems. In our hospitals, currently less than 1% of the patients have videos associated. With increasing improvements in technology there will be an increased storage of video clips in fetal imaging, but we are still far.

For this reason, we believe that recognition of 2d fetal images without relying on video is still of adamant importance for current clinical studies. Moreover, improving recognition and detection on images is the first pillar to improve the technology in general. These improvements will be the foundation for future tools that can assist the examination in real-time. In this study we release publicly a large dataset of images and a large evaluation of CNNs to encourage research on this field and move us closer to the goal of creating better A.I. tools for maternal-fetal medicine.

Recently, Cheng and Malhi\(^\text{18}\) demonstrated that transfer learning with CNNs can be used to classify abdominal 2D ultrasound images into 11 categories. They evaluated two CNNs (CaeNet and VGGNet) and compared their performance against that of a radiologist. In our work we follow a similar approach but applied to maternal-fetal US, which has its own particularities and is quite different from standard abdominal US. Furthermore, we perform a much larger evaluation and improve significantly overall recognition performance.

In this context, the goal of this study was two-fold: (1) evaluate the maturity of state-of-the-art CNNs to automatically classify 2D maternal fetal US and (2) the release of a large open-source dataset to promote further research on the matter. With this purpose in mind, we first collected a large maternal-fetal 2D US dataset. All images were manually labeled by two research technicians and a senior maternal-fetal clinician (B.V-A.). Finally, an exhaustive evaluation of state-of-the-art DL methods was performed using a benchmark protocol mimicking a real scenario, to judge how mature the technology is for its use in everyday clinical practice.

The contributions of this study are three-fold:

1. The collection of a large maternal-fetal ultrasound image dataset comprised of more than twelve thousand images from 1,792 patients in a real clinical setting. All images were labeled with 5 + 1 of the most widely used maternal-fetal anatomical planes by a senior maternal-fetal clinician, and further augmented with fetal brain planes, see Figs. 1 and 2 and Table 1. The dataset is the largest US dataset to date to our knowledge and represents a real clinical scenario with unbalanced data. The dataset will be made publicly available upon publication of this paper, to promote research on automatic maternal-fetal US recognition methods.

2. A comprehensive evaluation of different state-of-the-art CNNs on the newly collected dataset, see Table 2.

3. The direct comparison between state-of-the-art DL techniques and the classification performed by research technicians who perform the task daily in our hospitals, see Figs. 3 and 4. This comparison allows to judge the maturity of the technology and pinpoint areas that need improving, promoting future research. Results suggest for the first time that computational models can be used to classify common planes in human fetal examination.
Materials and Methods

Study design. The dataset was collected at BCNatal, a center with two sites (Hospital Clinic and Hospital Sant Joan de Deu, Barcelona, Spain), with large dedicated maternal-fetal departments handling thousands of deliveries per year. Images were acquired during standard clinical practice between October 2018 and April 2019. All pregnant women attending for routine pregnancy screening during second and third trimester were included in the study. Multiple pregnancy, congenital malformations or aneuploidies were excluded. Gestational age was computed from crown-rump length measurements on first-trimester US and ranged from 18 to 40 weeks. All the methods hereby explained were performed in accordance with the relevant guidelines and regulations and approved, together with the study protocol by the coordinator’s Institutional Review Board (Comité de ética de investigación clínica, ID HCB 2018/0031). All patients provided written informed consent to use US images for research purposes.

Image acquisition and labeling. Images were acquired from a total of six different US machines by several different operators with similar experience. US machines were three Voluson E6 (GE Medical Systems, Zipf, Austria), one Voluson S8, one Voluson S10 (GE Medical Systems, Zipf, Austria) and one Aloka (Aloka CO., LTD.). Images were taken using a curved transducer with a frequency range from 3 to 7.5 MHz (abdominal US) or a 2 to 10-MHz vaginal probe (used for cervical US screening in second trimester patients). Operators were instructed to avoid using any type of post-processing or artifacts such as smoothing, noise, pointers or calipers when possible. The remaining image settings parameters such as gain, frequency and gain compensation were left to their discretion. All images were stored in the original Digital Imaging and Communication in Medicine (DICOM) format.

In average each US study was comprised of 55 images. A Graphical User Interface (GUI) was developed in python (Python Software Foundation, USA) to allow a senior maternal-fetal specialist (B.V.-A.) to manually classify the images. The clinician selected images belonging to the five anatomical planes most widely used for maternal-fetal during fetal routine screening, see Table 1. Only images complying with the minimal quality requirements were selected by the clinician, excluding those with inappropriate anatomical plane (cropped or badly taken) and those with calipers. The dataset composition is clearly unbalanced (some classes are much more frequent than others) as is usually the case in real clinical scenarios.

Once all images labeled, in order to benchmark the performance of computational models on more fine-grained categorization, we further asked our clinical expert to extend labels of brain images with the specific

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Figure 1. Maternal-fetal US categories from our dataset: image examples, total number of images and frequency of occurrence (p). Fetus drawing was downloaded from openclipart.org, a creative commons repository of images for public domain use.
brain plane, divided into the three most common planes: Trans-ventricular, Trans-thalamic, and Trans-cerebellar. These three planes together account for 95% of all brain images, see Table 1.

Finally, two research technicians were asked to independently classify images from the second half of patients (test images, see below). These two research technicians were not clinical experts, but received extensive training in US classification. The performance of both technicians is used as baseline performance on the dataset, to judge the maturity of the computational methods for the automatization of the task.

**Final dataset & data public release.** To be able to measure false discovery rates of the methods benchmarked, an additional category called “Other” was created. This category contains a random subset of images not previously selected by the expert clinician, but avoiding images from the five main categories that were discarded for quality reasons (anatomical plane cropped or calipers). A total of 4,213 such other images were added; the final dataset being composed of 12,400 images.

To avoid ethical issues, all patient data from original DICOM images were fully removed by removing image header and images were stored in PNG (Portable Network Graphic) format (without compression to avoid losing quality). Since US images do not convey color information, images were stored as grayscale bitmaps.

The released dataset will contain all the information used in this study, namely:

1. All 12,400 images without header, in png format.
2. Fetal anatomical labels for each image (5 + 1 categories).
3. Fine-grained brain anatomical labels (3 categories) for each brain image.
4. Anonymized patient IDs for each image, where IDs are a consecutive 4 digit number ordering patients in ascending chronological order according to their first visit.

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**Table 1.** Maternal-fetal US dataset statistics: anatomical planes labeled, number of patients, number of images, US machines and Operators.
5. Training and Testing patients used in this paper.
6. US machine and Operator IDs for each image.
7. The two manual re-classification from both research technicians on the test images.

The dataset will be hosted in a dedicated website, where we will also maintain a list of published papers that use the dataset, reporting performance improvements.

**Methods used.** The goal of the study was to benchmark current classification techniques on the new dataset. In order to do so, and to mimick a real scenario, we ordered patients chronologically by the date of their first visit, and used all images from the first half of patients to train the classifiers and images from the second half of patients to evaluate the methods and report their performance. This resulted in a training set containing 7,129 images and a testing set containing 5,271 images (both with 896 patients).

**Simple baselines.** To judge the difficulty of the task, we first evaluated two simple non-DL classifiers. Both use as learning algorithm a multi-class Boosting algorithm. To process the images, the first one simply applies Principal Component Analysis to the image pixels, while the second uses classical Histogram of Oriented Gradients (HOG) features.

**CNN classifiers.** Then, we benchmarked a large set of the most widely used state-of-the-art classification CNNs, including many different architectures and a wide variety of depths, number of total parameters and processing speeds.

| Net               | Params | Layers | Speed (Hz) | top1-err(%) | top3-err(%) | class-acc(%) |
|-------------------|--------|--------|------------|-------------|-------------|--------------|
| VGG-M22           | 99 M   | 25     | 110        | 12.9        | 0.66        | 84.8±−9.3    |
| VGG-1622          | 134 M  | 54     | 40         | 7.9         | 0.55        | 92.1±−6.1    |
| MobileNet23       | 2 M    | 157    | 20         | 10.7        | 0.82        | 87.5±−9.6    |
| Inception-v324    | 22 M   | 318    | 12         | 6.5         | 0.34        | 93.5±−5.0    |
| ResNet-1825       | 11 M   | 73     | 66         | 7.6         | 0.47        | 92.5±−5.9    |
| ResNet-3425       | 21 M   | 129    | 38         | 7.6         | 0.76        | 92.5±−5.8    |
| ResNet-5025       | 24 M   | 177    | 25         | 6.8         | 0.32        | 93.1±−5.4    |
| ResNet-10123      | 43 M   | 347    | 10         | 6.7         | 0.23        | 93.4±−5.2    |
| ResNet-15225      | 58 M   | 517    | 5          | 6.5         | 0.21        | 92.8±−5.5    |
| ResNetXt-5028     | 23 M   | 179    | 25         | 7.3         | 0.34        | 92.7±−5.9    |
| ResNetXt-10128    | 42 M   | 348    | 13         | 6.5         | 0.55        | 94.0±−4.8    |
| SENet27           | 113 M  | 773    | 2          | 7.6         | 0.76        | 92.9±−5.9    |
| SE-ResNet-5027    | 26 M   | 256    | 14         | 7.6         | 0.76        | 93.3±−6.1    |
| SE-ResNet-10127   | 47 M   | 511    | 6          | 7.0         | 0.36        | 93.3±−6.1    |
| SE-ResNet-15227   | 47 M   | 511    | 3          | 7.5         | 0.32        | 92.7±−6.0    |
| SE-ResNetXt-5027  | 25 M   | 256    | 15         | 7.1         | 0.21        | 92.7±−5.7    |
| SE-ResNetXt-10127 | 47 M   | 511    | 6          | 7.1         | 0.27        | 92.7±−5.8    |
| DenseNet-12129    | 8 M    | 428    | 11         | 7.1         | 0.32        | 92.9±−5.8    |
| DenseNet-16929    | 14 M   | 596    | 7          | 6.2         | 0.27        | 93.6±−5.1    |
| Baseline1 (PCA + Boosting) | —     | —      | 41         | 39.6        | 10.4        | 54.7±−37.6   |
| Baseline2 (Hog + Boosting) | —     | —      | 28         | 25.5        | 5.2         | 68.6±−28.8   |

Table 2. Results of the wide variety of classification CNN tested for maternal-fetal common planes recognition. DenseNet-169 is the best performing model in terms of top-1 error. Inception and ResNetXt-101 are the best performing models taking into account trade-off between speed and performance.
convolutional layer of all nets was adapted to work on 1 channel after training on ImageNet, using the average of each one of the first 3 convolutional channel filters. Lastly, Fully-Connected layer of each network was adapted to output 6 classes instead of ImageNet’s 1,000. Batch-normalization was used for all nets after convolution layers. No further weight regularization was enforced. Input US images were converted from integer in range \([0, 255]\) to single float precision in \([-1, 1]\) range using the norm of all training images.

Statistical analysis. Main results. Each one of the methods was applied to the test images, storing full probability scores. Then, top-1 error and top-3 errors with respect to test labels produced by our clinician were computed. Top-1 error (1-accuracy) indicates the percentage of miss-classified images and was considered the main metric. Top-3 error was used to judge how often the true class was predicted as one of the 3 most likely classes (out of the 6 total classes), to judge the net’s margin on miss-classifications. Then, full confusion matrices were also computed and the mean and standard deviation of the diagonal (class-acc) were shown. Matrix columns are the prediction from (a, b) our two research technicians and (c) DenseNet-169 model.

Figure 3. Results on common planes classification. Confusion matrices on the 896 test patients (5,271 images) are shown. Matrix rows show the true class, labeled by our expert maternal-fetal clinician. Top-1 error and mean \(\pm\) std of the diagonal (class-acc) are shown. Matrix columns are the prediction from (a, b) our two research technicians and (c) DenseNet-169 model.
Fine-grained brain labels. We used the best performing model CNN according to Table 2 results (Densenet-169) to further test performance on fine-grained brain classification. We used the original training and testing patients, keeping only those that had at least one image of the three brain sub-planes. The result was a train set composed of 592 patients and 1,543 images, and a test set having 536 patients and 1,406 images. Then, the training set was augmented with 500 random images from other planes. The net was trained and tested on the new data, using the same test images to report research technicians’ performance. Results are shown in Fig. 4.

Ablation study. For completeness, using one of the nets (Inception) showing best trade-off between speed and performance according to Table 2 results, we performed an ablation study to analyze the effect that some technical details have on performance. The following was evaluated:

1. Different CNN training: We tested performance vs some training parameters, such as not pre-training models on ImageNet, performing only fine-tuning of the last layer, removing data augmentation and using...
a data balancing approach. Results are shown in Table 3.

2. Performance vs number of training patients/images: We tested performance vs number of training patients/images. We created 8 additional training sets by removing from the original training set a hundred patients at a time, and each was used to train the CNN. Testing was performed on the same, unchanged test dataset containing 896 patients. Results are shown in Fig. 5.

3. Transferability: We created several different training and test sets, partitioned by which US machine and operator had collected each image, using only US machines and Operators that have at least 2,000 total images. The CNN (Inception) was trained and tested on each set and compared with normal model trained on images from all US machines and operators. Results are shown in Table 4.

Results

Maternal-fetal US dataset. Table 1 summarizes the characteristics of the final dataset. A total of 1,792 patients were recruited. Some of them had a longitudinal follow-up, having a total of 2,087 distinct US studies. Images were classified into the five anatomical planes most widely used for maternal-fetal during fetal routinary screening, plus an extra category called “Other” containing other planes. Furthermore, brain images were categorized into their sub-plane using three categories. Images were collected from several ultrasound machines and
by different operators. The dataset is comprised by a total of 12,400 images. Since images were collected prospectively from a real clinical scenario by different US machines and operators, classes show high variability and have different probabilities of appearance, see Table 1. Figures 1 and 2 show visual examples of the type of US images present in the dataset for each category.

**Classification results.** Table 2 shows the main results of each method on the test set, comprised of 5,271 images from the second half (896) of patients. Best performing net is DenseNet-169 with a 6.2% top-1 error, 0.27% top-3 error and 93.6% average class accuracy. Taking into account the trade-off between performance and speed/size, both Inception and ResNetXt-101 achieve similar performance (6.5% top-1 error) while doubling DenseNet-169’s speed. In general, variation in performance is low, with the difference between lowest and highest top-1 errors being 6.7%.

More modern architectures do not always perform better than older ones: while DenseNets work well, Squeeze-Excitation variants of classical ResNet networks sometimes perform worse than the classical architectures. As for depth, deeper nets usually perform better in general. The non-DL baselines are clearly much weaker, reaching top-1 errors above 25%.

**Ablation study.** Using one of the nets showing best trade-off between speed and performance in previous section (Inception), we performed an ablation study to analyze the effect that some technical details have on performance. Table 3 and Fig. 5 show the results:

1. No pre-training: If the network is directly trained from scratch on our dataset, top-1 error increases 8% when compared with using a pre-trained Imagenet model. This shows the importance of pre-training models on a very large dataset and that convolutional filters learned on natural images are indeed transferable to US.

2. Last layer training only: If the pre-trained network is only fine-tuned (only last convolutional branch and final fully connected classification layer are allowed to change) top-1 error increases 4% when compared with a full re-training of the net. This shows that re-training on our dataset is more important on deeper layers, but that allowing the entire net to change is beneficial.

3. No data augmentation: Similar to what observed in natural images, data augmentation during training is beneficial: removing it makes top-1 error increase a 1.6%.

4. Data balancing: Using a class re-weighting approach during training to help the model with class unbalance did not improve performance, in fact top-1 error increased slightly by 1%.

5. Number of training images/patients: Fig. 5 shows the performance of Inception model on the test set as a function of the number of patients used for training. Errors drop significantly as soon as a few hundred patients are seen during training, but maximum performance is reached only when all images are used.

**Computational model transferability.** A key factor for the applicability of automatic computational methods in medicine is the transferability of results between centers, different equipment and operators. We tested how well models built using images exclusively from one machine/operator can translate to the rest. Results are shown in Table 4, where rows correspond to the type of images used for training and columns to the type of test images. This experiment had two relevant results:

1. It is always preferable to train the model on images from all sources (all US machines and operators). Even when evaluating on images from a specific US machine/operator, a model trained from all sources yields better performance than a model trained specifically for that US machine/operator.

2. Both US machines and operators have an important impact in performance. However, of the two, US machines have by far the most important impact. Clearly, the computational model can quickly overfit to the type of US images seen, and results when trained only on a machine and tested on a different can show almost a two-fold increase in error rates.

**Comparison vs human.** We directly compare the performance of the best computational model (DenseNet-169) against that of our research technicians, using images from all 896 test patients. Full confusion matrices for the research technicians and best computational model are shown in Fig. 3. Both achieve similar performance, with top-1 errors of 5.1% and 6.5% for the technicians and 6.2% for the CNN. The CNN reaches close to perfect performance on 2 of the 6 classes (Brain and Cervix), but performs slightly worse than both technicians on the other 4 classes (Other, Abdomen, Femur and Thorax). Femur seems to be especially hard for the CNN; we believe this is due to the fact that Other category contains other bones (Humerus, Radius, Tibia, etc.) which can look very similar. As for processing time, the computational model processes images at 7 Hz (0.14 seconds per image), while research technicians require an average of 3.5 seconds to classify each image using our GUI.

**Fine-grained brain categorization.** Finally, we also evaluate performance of the best computational model (DenseNet-169) on fine-grained brain categorization and compare its performance against that of our research technicians, using all brain images from our test patients (536 patients, 1406 images). Results are shown in Fig. 4. Errors are much higher than before, showcasing the difficulty of the task. Technicians reach top-1 errors of 15.9%
Furthermore, the computational model classifies images 25 trained to perform the task, meaning that for the first time this technology is reported to be mature enough as general visual recognition from standard photographs can also work for maternal-fetal US recognition. The best available to promote research on automatic US recognition methods.

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Data availability
All data associated with this study is available in the main text. Furthermore, the entire ultrasound dataset will be made publicly available upon publication from a dedicated website together with the list of papers using the dataset, to report performance improvements.

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Author contributions
X.P.B.-A. was the person in charge of the project. He supervised data collection and labeling, designed and ran most of the experiments and wrote the paper. D.C.-G. supervised dataset collection and storage, designed all software needed for labeling and helped running experiments. B.V.-A. managed the clinical side, labeled every image carefully and expertly and provided feedback on the design of the study and the manuscript. E.B.-C. helped with the study design, supported all authors and helped writing sections of the paper. E.E., F.C. and E.G. acted as clinical supervisors, helping with the study design, the clinical side and providing feedback for the writing of the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
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