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CYCLE GAN-BASED DATA AUGMENTATION FOR MULTI-ORGAN DETECTION IN CT IMAGES VIA YOLO

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ABSTRACT

We propose a deep learning solution to the problem of object detection in 3D CT images, i.e. the localization and classification of multiple structures. Supervised learning methods require large annotated datasets that are usually difficult to acquire. We thus develop a Cycle Generative Adversarial Network (CycleGAN) + You Only Look Once (YOLO) combined method for CT data augmentation using MRI source images to train a YOLO detector. This results in a fast and accurate detection with a mean average distance of 7.95 ± 6.2 mm, which is significantly better than detection without data augmentation. We show that the approach compares favorably to state-of-the-art detection methods for medical images.

Index Terms— multi-organ detection, image synthesis, data augmentation, medical imaging

1. INTRODUCTION

Object detection consists in localizing structures in images using bounding boxes and classifying them. Many approaches have been proposed relying on statistical [1, 2, 3] or deep learning [4, 5, 6] techniques. In spite of the success of existing methods, only a few works have employed deep learning for multi-organ detection in medical images [7, 8]. Object detection is a prerequisite in many radiological procedures such as patient screening and diagnosis which implies localizing anatomical structures or lesions. Most of object detection models in medical images are designed for single-object detection [9, 10]. Our method aims at detecting multiple organs in 3D CT images. Detection should furthermore be time efficient when processing large datasets. We choose the YOLO detector [5] as a basis in our work. It has been shown to offer a good precision vs speed trade-off for natural images compared to other deep detectors. Supervised deep learning requires large training datasets which are not always available for medical images. This is because such images are expensive to obtain, compared to natural images. Furthermore, manual annotation of medical images, especially in 3D, is very time consuming. We propose to expand a baseline training dataset via data augmentation. Most data augmentation approaches apply transformations to images such as rota-

tions and translations [11]. Transformed data are then added to the training set. As opposed to this technique, we use a CycleGAN [12] as an unsupervised method that synthesizes images from annotated source images of a different modality. We show that the CycleGAN+YOLO combination yields an efficient approach to augment and detect multiple structures.

2. RELATED WORKS

2.1. Object detection

Supervised object detection aims at classifying object instances from predefined annotations and localizing them in images. Deep learning-based detection methods can be categorized into two approaches: *two-stage* and *one-stage*. Models in the former approach are trained separately for two tasks: detection of regions of interest and classification/localization of objects. Region-Based Convolutional Neural Network (R-CNN) methods [13, 4] are among the best-performing ones. They use modules for feature extraction, classification/regression and region proposal, the latter being a separate convolutional network in [4]. In the one-stage detection approach, a single network is trained for both classification and localization, no region proposals are created. You Only Look Once (YOLO) [5] and Single Shot multi-box Detector (SSD) [6] are both popular detection methods in this category. YOLO is a fast real-time object detector with an optimized network architecture. SSD introduces multi-reference and multi-resolution techniques for higher precision.

In medical image analysis, best-performing statistical detection approaches are based on regression forests [2] which are applied in a cascaded, global-to-local fashion in [1, 3] augmented by a shape prior in the latter work for improved precision. Deep methods however are quickly gaining ground. YOLO has been used for detection on retinal images [14], and SSD for liver lesion detection in CT [9]. Among recent works investigating deep multi-organ detection we mention [7] where two convolutional networks, one for classification and another for bounding-box regression, were trained and tested separately for few dozen structures in 2D slices of 3D CT images, and [8] which employs a convolutional network, trained and tested on chest CT structures simultane-

ously, which is augmented with spatial pyramid pooling to analyze 2D slices of different sizes.

2.2. Cross-modality Image Synthesis

A rich body of work that uses Generative Adversarial Networks (GAN) for synthesizing images in one modality from those in another has been proposed [11]. CycleGAN was proposed in [12] and became one of commonly used approaches in synthetic medical image applications. Importantly, it can be used in the case of unpaired data, which is particularly useful in our application, since it is usually not possible to have images of different modalities for the same patient under the same conditions. In other words, instances are not mutually mapped between source and target domains, and therefore no registration is required. CycleGAN was employed in [15] to generate brain CT images from MRI images, and in [16] to generate lung MRI images from CT images in lung tumor segmentation. Our work is inspired by [17] which aims to segment a single organ (the liver) without having ground-truth annotations for the target modality. A CycleGAN is used to generate target modality images from labeled source images. Source labels are then transferred to the target. As already stated, our work aims at multi-organ detection.

3. METHOD

As shown in Figure 1, our workflow has 2 stages: cross-modality synthesis with CycleGAN [12] and multiple-organ detection with the YOLO algorithm [5]. YOLO was selected as the detector due to its speed and precision, as mentioned in the previous section. This approach starts by splitting an image into $S \times S$ cells. Each grid cell predicts three components: (1) coordinates (x, y, w, h) of B bounding boxes, (2) a confidence score $P(object)$, and (3) a class probability for C categories conditioned on the presence of an object in the bounding box. In our work, we use the third version of YOLO (YOLOv3) [18]. Its architecture is composed of 53 convolutional layers (Darknet-53). It makes predictions at three different scales. For a more stable prediction, scale-dependent box priors are used. These are learned from the training dataset. YOLOv3 also adds cross-layer connections between each two prediction layers except for the output layer. In our experiments we train and apply YOLO on 2D full-resolution axial cross-sections of 3D images due to GPU memory restrictions and the complexity of the network model. A low resolution 3D approach would incur significant loss of precision for small structures. We train YOLO with 450 epochs and a decreasing learning rate.

CycleGAN [12] is an unsupervised deep learning method which allows bidirectional translation between the source X and the target domain Y . It uses two generator networks G_1, G_2 such as $G_1 : X \rightarrow Y$ and $G_2 : Y \rightarrow X$, each associated with a discriminator network, D_1 and D_2 following

an adversarial training. G and D networks compete against each other. D works as a binary classifier attempting to distinguish between the synthetic and the real target image, while G seeks to deceive the discriminator by improving the quality of the synthetic output image. The input of the generator network G is a source domain image $x \in X$ and its output is a synthetic image, $\hat{y} = G(x)$. The inputs of a discriminator D are the synthetic output \hat{y} and an unpaired random image from the target domain $y \in Y$. As for the architectures, the generator has an encoder, a transformer (a Residual Network in practice) and a decoder. The discriminator model is implemented as a PatchGAN model [12] which aims at classifying images as real or synthetic. The CycleGAN was trained using 200 epochs. We fixed the learning rate on 0.0002 for the first 100 epochs, then we linearly decay it until reaching zero over the rest. Synthetic images that are generated using CycleGAN are then used, along with the annotations of source images, to augment the training datasets for YOLO detectors.

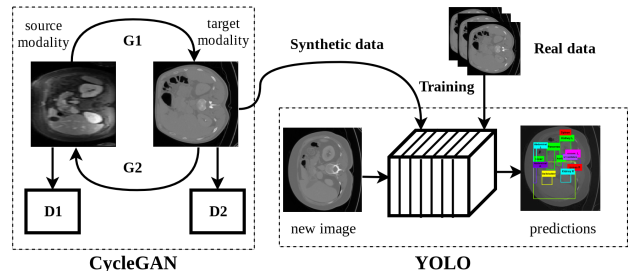


Fig. 1. The proposed framework : CycleGAN (image synthesis) + YOLO (multi-organ detection).

4. EXPERIMENTAL RESULTS

4.1. Datasets and pre-processing

The data used in this study come from the Visceral Anatomy Benchmarks [19] and involves 2 datasets: (1) a *Gold* dataset, the annotations of which were created using manual segmentation, and (2) a *Silver* dataset, the labels of which were obtained by merging the segmentations produced by the algorithms of benchmark participants. Both datasets consist of unpaired 3D contrast-enhanced thoracic-abdominal CT and abdominal MRI images providing 20 and 15 structure annotations respectively. Mean image dimensions are $512 \times 512 \times 438$ voxels for CT and $312 \times 72 \times 384$ voxels for MRI. The Gold dataset provides 20 patients per modality. We chose 30 patients per modality in the Silver dataset. To reduce the computational cost, all our experiments are carried out in 2D axial slices of original 3D images. We use the provided segmentation annotations to define 2D bounding-box annotations to train YOLO detectors. For the experiments on cross-modality image synthesis, we crop CT images in both datasets around the abdomen and resize them to 320×320 pixels. This is because the thorax is absent in MRI images.

4.2. Performance metrics

We perform quantitative evaluations for two tasks: multiple-organ detection and cross-modality image synthesis. We use mean Average Precision (mAP) to select the best detector model over a validation set in a k -fold cross-validation procedure. This metric is conventionally computed as the area under the precision-recall curve. The best detector is then used to create the 2D bounding-box predictions on the test set, from which 3D bounding-boxes are constructed simply by taking maximum coordinates. We measure the 3D detection precision with respect to ground truth as the average distance over the 6 faces of the reconstructed 3D detection and the annotation bounding boxes.

For experiments on image synthesis, as in [20], we evaluate reconstruction fidelity as an indicator of synthesis quality via the Structural SIMilarity (SSIM) metric.

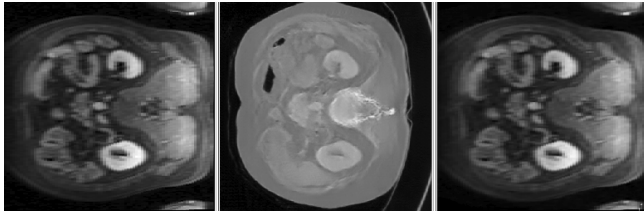


Fig. 2. Qualitative results of cross-modality generation (from MRI to CT image). The real MRI image (left), the generated CT image (center) and the reconstructed MRI image (right).

4.3. Cross-modality image synthesis

An example of CycleGAN MRI to CT image translation is presented in Figure 2. It shows the consistency of translated structures with CT enhancement patterns, e.g. bright vertebra, kidneys brighter than muscles etc. To perform a quantitative evaluation of CycleGAN performance, we compute the SSIM between a source image x and its reconstruction $G_1(G_2(x))$. For the MRI to CT translation, we have a mean SSIM of 0.97 (averaged over all patients). This evaluation was performed on Gold dataset images with a model trained on those of the Silver dataset.

4.4. Multi-organ detection

Multiple-organ detection was evaluated on the Visceral Gold dataset using 10-fold cross-validation under two scenarios, without and with data augmentation. For the latter scenario, a CycleGAN trained on the Silver dataset was used to translate MRI images in the Gold dataset into CT which were used to augment the training data in each of the 10 folds. Test data are identical in both scenarios. For each fold, the model that yielded the best detection performance (measured by mAP) is selected. As previously stated, detection precision is measured in 3D on reconstructed bounding boxes. Results averaged over all images are shown in Table 1. We observe

that distances corresponding to large organs such as the spleen (6.8 mm) and the right kidney (5.6 mm) are satisfying, as opposed to organs difficult to detect such as the pancreas (14.3 mm) and the right psoas major muscle (16.6 mm). The CycleGAN+YOLO scenario yields better results for most organs. The mean average distance in this case is 7.95 mm as compared to YOLO alone 8.66 mm. This improvement is statistically significant ($p = 0.046$ on a paired one-sided t-test). Table 1 also indicates that the standard deviation is high for several organs (e.g. the right kidney 12.9 mm). A careful examination of predictions confirms that this is due to outliers in the detection. Figure 3 shows an example of multi-organ YOLO detection for an axial CT image. It shows in particular that the bounding boxes are well centered on the organs, even for smaller ones.

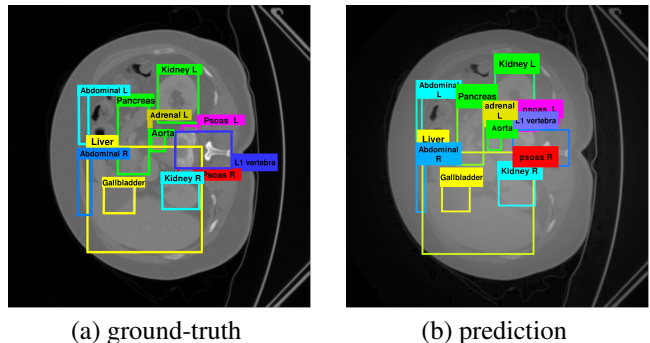


Fig. 3. 2D multi-organ detection on an axial CT image.

Table 1. YOLO (mean dist. 8.66 mm) vs CycleGAN+YOLO (mean dist. 7.95 mm) comparison on per organ mean distance.

	Pancreas	Gallbladder	Bladder	Vertebra L1	Kidney R
YOLO	14.3 ± 10.4	6.9 ± 10.9	4.0 ± 1.2	6.2 ± 3.5	5.6 ± 12.9
CycleGAN + Y.	10.6 ± 5.2	7.4 ± 11.2	4.5 ± 1.6	5.8 ± 3.3	5.9 ± 12.4
	Kidney L	Adrenal R	Adrenal L	Psoas R	Psoas L
YOLO	4.7 ± 5.8	6.6 ± 6.5	8.1 ± 8.4	16.6 ± 13.4	12.7 ± 7.1
CycleGAN + Y.	4.3 ± 4.8	6.3 ± 5.9	7.8 ± 8.7	11.8 ± 6.9	12.8 ± 5.7
	Abdominal R	Abdominal L	Aorta	Liver	Spleen
YOLO	13.6 ± 12.1	11.9 ± 7.3	4.0 ± 3.0	7.4 ± 4.4	6.8 ± 7.0
CycleGAN + Y.	11.9 ± 6.7	12.2 ± 7.7	3.9 ± 2.6	6.9 ± 3.4	6.5 ± 6.2

Regarding the running time of YOLO, we process an entire CT volume in 8 s. All our models are trained and tested on NVIDIA Tesla V100 GPUs with 32 GB of main memory.

Table 2 compares our performances with those of state-of-the-art methods [1, 2, 3] applied to abdominal organs in contrast-enhanced CT images. This comparison is indicative as it was not possible to evaluate our method on the same datasets. Table 2 shows that YOLO and CycleGAN+YOLO yield best performances for the majority of studied organs in comparison with other methods.

Table 2. Comparison with state-of-the-art methods based on mean distances per organ.

Method	Liver	Kidney R	Kidney L	Spleen	Gallbladder
Cuingnet [1]	12.2 ± 4	6.4 ± 4	6.8 ± 6	9.0 ± 5	11.8 ± 8
Criminsi [2]	14.0 ± 5	13.2 ± 6	12.3 ± 7	14.2 ± 6	15.5 ± 8
Gauriau [3]	10.7 ± 4	5.6 ± 3	5.5 ± 4	7.9 ± 4	9.5 ± 4
YOLO	7.4 ± 4.4	5.6 ± 12.9	4.7 ± 5.8	6.8 ± 7.0	6.9 ± 10.9
CycleGAN + Y.	6.9 ± 3.4	5.9 ± 12.4	4.3 ± 4.8	6.5 ± 6.2	7.4 ± 11.2

5. CONCLUSION AND FUTURE WORK

In this study, we proposed a CycleGAN+YOLO combination for data augmentation to train a multi-organ detector for CT images. Our work counters the scarcity of labeled medical data which hinders the supervised learning of deep networks by using a CycleGAN to generate synthetic images to augment training data. We showed that this approach achieves accurate detection with mean average distance of 7.95 ± 6.2 mm which constitutes a significant improvement over YOLO detection alone. Further improvement of our results implies the development of a strategy that rejects detection outliers. This can be done by encoding anatomical constraints of proximity or adjacency as new terms in the loss function of the detector, to be optimized simultaneously with regression and class-probability terms.

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