

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Characterization of Retinal Fluid in OCT images

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WORKING VERSION



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Resumo

Abstract

UN Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) provide a global framework to achieve a better and more sustainable future for all. It includes 17 goals to address the world's most pressing challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice.

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The specific Sustainable Development Goals mentioned have the following names:

SDG 7 Ensure access to affordable, reliable, sustainable and modern energy for all

SDG 8 Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

SGD	Target	Contribution	Performance Indicators and Metrics
7	7.1	Enhancing the efficiency of SCADA systems can help increase the reliability of solar energy production, facilitating universal access to clean energy.	Percentage of solar plants with improved ...
	7.2	Improving the management of solar plants helps enhance the efficiency and reliability of renewable energy ...	Increase in renewable energy share ...
8	8.1	Enhancing renewable energy infrastructure promotes resilience against climate-related hazards and supports sustainable energy sources.	Increase in resilience metrics ...

Acknowledgements

David Castanho Terroso

“Our greatest glory is not in never falling, but in rising every time we fall”

Confucius

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List of Acronyms

AMD	Age-related macular degeneration
BM	Bruch's membrane
CNN	Convolutional neural network
CT	Computed tomography
DME	Diabetic macular edema
GAN	Generative adversarial network
GT	Ground truth
HR	High-resolution
ILM	Internal limiting membrane
IRF	Intraretinal fluid
MAE	Mean absolute error
MRI	Magnetic resonance imaging
MSE	Mean Square Error
LR	Low-resolution
OCT	Optical coherence tomography
ONL	Outer nuclear layer
PED	Pigment epithelial detachment
PSNR	Peak signal-to-noise ratio
ROI	Region of interest
RPE	Retinal pigment epithelium
RVO	Retinal vein occlusion
SR	Super-resolution
SRF	Subretinal fluid
SSIM	Structural similarity index measure

Chapter 1

Introduction

The vision is the human's most important and complex sense, playing a critical role in our orientation in the world [1]. However, the health of the retina, an important part of the eye, can be compromised by multiple diseases, that lead to fluid accumulation in it. The characterization of the fluid present in the retina is important to assess the progression of diseases such as age-related macular degeneration (AMD), diabetic macular edema (DME), and macular edema secondary to retinal vein occlusion (RVO) [2].

AMD affects the macular region of the retina, leading, in later stages, to a significant and permanent loss of central visual acuity, which has a severe impact on the patient's quality of life. In patients with AMD, the formation of new blood vessels can occur, which leak fluid, lipids, and blood into the retina, resulting in the formation of retinal fluid [3]. It is one of the leading causes of visual impairment with an expected effect on 300 million people by 2040 [4].

In patients with diabetes mellitus, DME represents the most common cause of visual impairment, affecting approximately 150 million people worldwide, as of 2015. It is anticipated that this number will increase as the prevalence of diabetes in developed countries is growing [5]. The fluid accumulation is caused by a disruption of the blood-retinal barrier, which allows fluid to accumulate in the intraretinal layers of the macula, resulting in retinal thickening (edema) [6, 7].

Affecting 16 million people worldwide, RVO represents a significant cause of vision loss in older individuals. The occlusion of the retinal vein can result in swelling of the optic disc, which leads to a reduction in visual acuity [8].

The presence of intraretinal fluid (IRF) is a defining criterion of DME and RVO, while two in every three patients with AMD present this type of fluid. The majority of patients with AMD and 30% of the patients with DME and RVO have subretinal fluid (SRF). Pigment epithelial detachments (PED) occurs more frequently in patients with AMD [2].

Therefore, retinal fluids are important for the classification and progression of these diseases, and can be observed through retinal optical coherence tomography (OCT) [2]. OCT is a non-invasive imaging technique that analyzes the light behavior (such as its reflection, absorption, and time-of-flight) to estimate the spatial dimensions of the tissue's structure [9]. This allows for *in vivo* visualization of the individual retinal layers within the posterior segment of the eye. An

OCT is composed of multiple consecutive cross-sectional 2D images that, when stacked, form a volumetric representation of the posterior segment. Each of these two-dimensional images is referred to as B-scans and an example can be seen in Figure 1.1. The resolution is sufficiently high to assess the tissue integrity, the retinal layers, and the fluids present [10, 11]. There are multiple devices used for the acquisition of OCT volumes, resulting in different image attributes across the same technique, such as interslice distance, image quality, and appearance [2].

The classification of the fluid is dependent on its location within the retina. There are three different categories: IRF, which is situated in the inner and outer layers of the retina; SRF, positioned between the outer nuclear layer (ONL) and the retinal pigment epithelium (RPE); and PED, which appear beneath the RPE [2]. Figure 1.1 shows the characteristics and positions of these fluids on an OCT B-scan and Figure 1.2 exhibits the retinal layers in the OCT scan of a healthy patient.

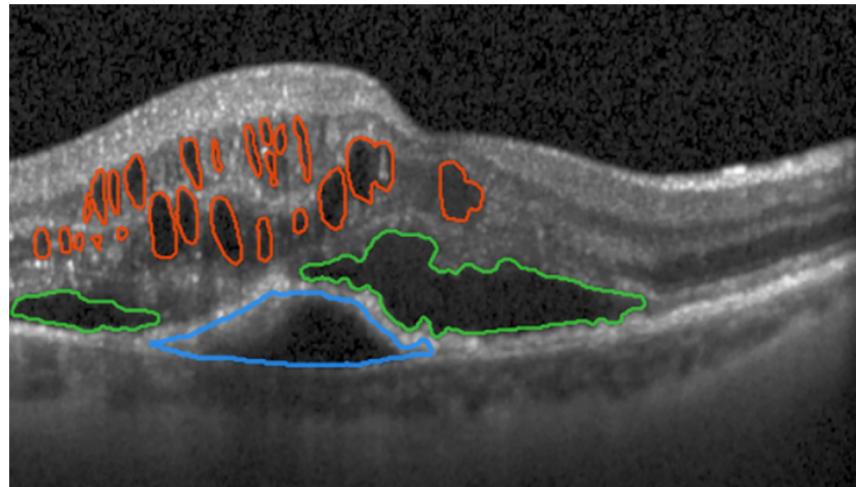


Figure 1.1: The three distinct fluid types on an OCT B-scan: IRF in red, SRF in green, and PED in blue [2].

By segmenting the fluids detected in the B-scans, their volume can be estimated and used as a progression marker of the mentioned retinal diseases. However, manual segmentation is laborious, expensive, and prone to bias, which motivates the search for automatic methods [11].

In OCT imaging, the precision of the estimated volume is not only dependent on the quality of the segmentation, but also on the interslice distance [13]. It is seen in other imaging techniques that the performance of the segmentation is improved when the neighboring slices are used as input. Consequently, the reduction in interslice distance and improvement of the resolution along this axis, betters the performance of models that include information from adjacent slices [14]. Given that the interslice space is reduced, the estimated segmented volume will also be closer to the real fluid volume.

Considering the previous statements, the dissertation general objective is to conduct an analysis of retinal OCT scans, classifying the retinal fluids in three distinct types (IRF, SRF, and PED) and quantifying their respective volumes. Another important objective is to increase the inter-slice resolution of the OCT volumes, with the aim of improving the fluid volume estimation. The

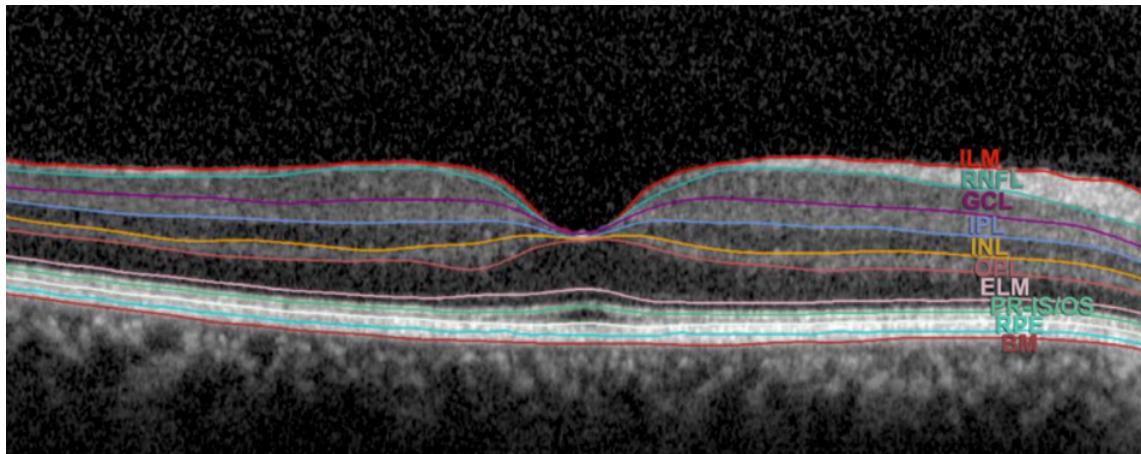


Figure 1.2: OCT scan of the retinal layers [12].

BM, Bruch's membrane; ELM, external limiting membrane; GCL, ganglion cell layer; ILM, internal limiting membrane; INL, inner nuclear layer; IPL, inner plexiform layer; ONL, outer nuclear layer; OPL, outer plexiform layer; PR-IS/OS, photoreceptor inner segment/outer segment; RNFL, retinal nerve fibre layer; RPE, retinal pigment epithelium.

specific objectives were determined as follows:

1. Develop different 2D deep learning models for multi-class segmentation of retinal fluids (IRF, SRF, and PED) in OCT volumes.
2. Compare the best performing 2D model with a previously implemented 2.5D model.
3. Evaluate the performance of the best segmentation model and estimate the volume of each fluid using the masks predicted by it.
4. Use of a generative model for synthesizing intermediate slices in OCT volumes, generating one or more slices between two real slices to improve the interslice resolution of the volume, while assessing the quality of these generated images.
5. Investigate the impact of intermediate slices synthesis on the fluid volume estimation by the segmentation models.

Apart from the “Introduction”, the dissertation is composed of the following chapters: “Literature Review”, “Methods”, “Results and Discussion”, and “Conclusion”. In the “Literature Review” chapter, an analysis is performed on the latest papers in the field of retinal fluid segmentation using 2D deep learning networks, as well as the latest publications on interslice resolution enhancement. The “Methods” chapter details the selection of the dataset for the experiments performed during the dissertation, alongside with an insightful description of the experiments. In the “Results and Discussion” chapter, the results from each experiment are shared, showing the performance of each model in their respective task, while explaining the performance differences between experiments, comparing them to the literature. Finally, the “Conclusion” shows the main findings from the experiments performed and suggests directions of further research.

Chapter 2

Literature Review

For this dissertation, research was conducted to find the most recent trends in 2D fluid segmentation of OCT volumes using deep learning and in the use of generative models in the intermediate slice synthesis.

2.1 Fluid Segmentation

In the fluid segmentation state-of-the-art research, articles were retrieved using the methodology of a systematic review. The next subsection details the retrieval process and the criteria for inclusion and exclusion of the articles. “[2.1.2 Literature Review](#)” shows the trends on the methodologies utilized for fluid segmentation.

2.1.1 Search Strategy

The search query was defined as: ““OCT” AND “segmentation” AND (“deep learning” OR “CNN” OR “neural network”)”. Using the query, papers were retrieved from four different databases: 398 articles from PubMed, 105 from IEEE, 125 from ScienceDirect, and 80 from ACM.

In the process of collecting the papers, those published over the previous five years and regarding 2D or 2.5D fluid segmentation in OCT volumes were included. Additionally, conferences proceedings, articles not written in English, and articles for which the full text was not accessible were excluded.

A total of 708 articles were initially identified, of which 133 were duplicates. Afterwards, 575 articles were subjected to screening, based on their titles and abstracts. These articles were analyzed in accordance with the inclusion and exclusion criteria, resulting in the removal of 499 papers. Of the remaining 76 articles for the full-text screening, 20 met the established criteria. These final articles represent the state-of-the art in 2D deep learning fluid segmentation in OCT volumes included in this dissertation.

2.1.2 Literature Review

The selected papers can be divided into two broad groups, according to the type of segmentation: binary segmentation [15, 16, 17, 18, 19, 20], where the fluid is classified in one whole class, and multi-class [21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34], where the segmented fluid is classified in two or more classes (namely IRF, SRF, and PED). We have also considered other criteria to group the papers, such as the segmentation architecture, and the use of retinal delimitation, as shown in Figure 2.1.

In binary segmentation, the approaches to the segmentation problem are simpler, but include both convolutional neural network (CNN) [16, 17, 18, 19, 20] and transformer solutions [15]. The CNN solutions differ among them, depending on the modules that constitute each network, but all are inspired by the U-Net [35]. In Figure 2.2, an instance of a CNN used for binary fluid segmentation is shown.

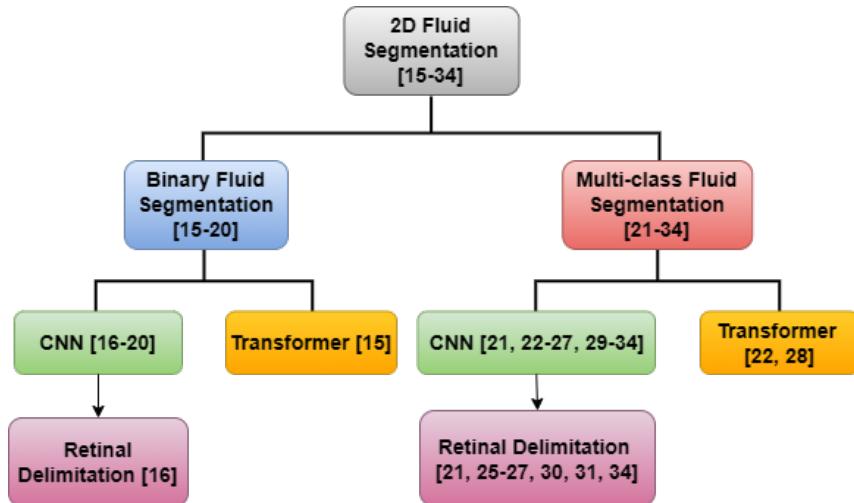


Figure 2.1: Grouping of the articles included in the literature review.

Pawan et al. [16] is the only paper in binary segmentation that restricts the input of the segmentation CNN to the content within the retinal layer. This approach is frequently observed in the papers focused on multi-class segmentation. In this article, this is achieved by performing a retinal layer segmentation and assigning all the values outside the boundaries to zero. The result of this operation is an input for the segmentation CNN. The removal of irrelevant information surrounding the retina simplifies the learning process and improves the model's focus on essential information [34].

In the framework proposed by Liu et al. [17], the slice's fluid mask and distance map are generated. The distance map consists of the predicted distance of each pixel to the background or retinal tissue, with only the values above a specified distance threshold being kept. This is achieved through the use of a double-branched network, where the encoder is the same, while the decoders vary. One encoder is responsible for generating the fluid segmentation map, while

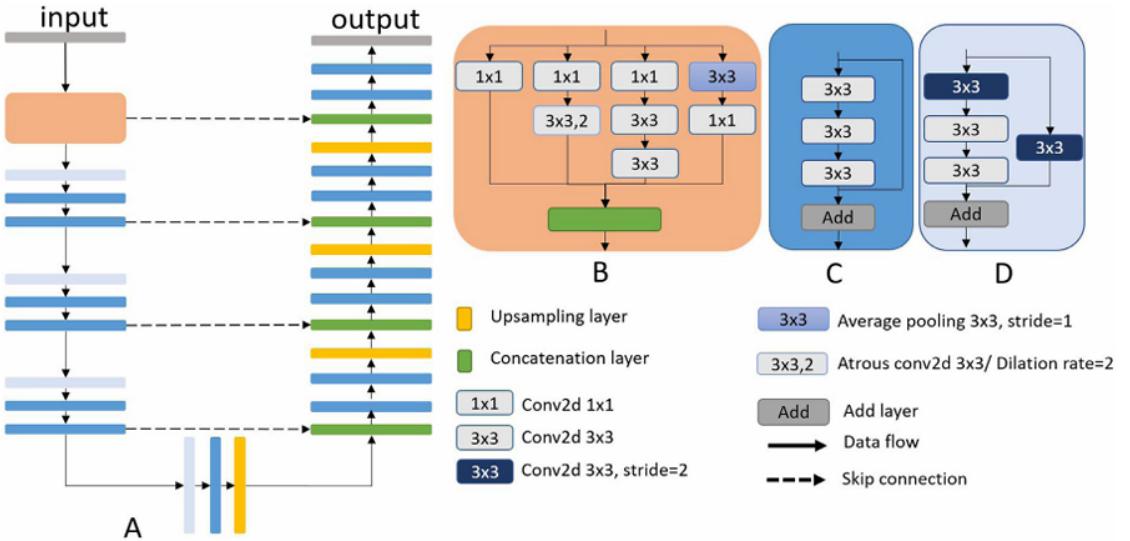


Figure 2.2: Example of a CNN architecture used in fluid binary segmentation. Image A depicts the neural network architecture. B shows the used multi-scale block, while C and D exhibit the residual convolutional blocks [18].

the other predicts the distance map. The intersection between these outputs forms the final segmentation. This approach mitigates the issue of inappropriate merging of small and proximate fluid regions, as the distance branch is better than the fluid segmentation network in discerning the boundaries that delineate fluid regions.

Resorting to generative adversarial networks (GANs), Wu et al. [20] make images from different vendors, visually similar to the images of a singular, specific vendor. Subsequently, a U-Net, which has extensively been trained on images from the specific vendor, is used for segmentation. This approach is intended to reduce the burden of learning the segmentation on multiple vendors by ensuring that all volumes are similar to one in which the segmentation model performs well. Similarly, the multi-class segmentation framework proposed by Li et al. [23] was designed based on the same idea.

CNNs inspired by the U-Net can also be combined with transformers in the context of image segmentation. While CNNs capture the information from local receptive fields, visual transformers integrate features from global receptive fields. Despite being more prevalent in multi-class segmentation frameworks, in this paper by Quek et al. [15], the visual transformers are located between the encoder and decoder paths, thus incorporating features from both receptive fields in the encoding branch.

The majority of the papers included in this review perform multi-class segmentation models, therefore presenting more diverse implementations. While all these articles segment two or more fluids, Hassan et al. [27] and Padilla-Pantoja et al. [32] also segment other biomarkers. Similarly to binary segmentation, the multi-class segmentation papers can also be divided according to the presence [22, 28] or absence [21, 23, 24, 25, 26, 27, 29, 30, 31, 32, 33, 34] of transformers in the segmentation network. All the papers that have transformers in their framework, combine them

with CNNs.

Similar to what was developed in Quek et al. [15], Liu et al. [22] have integrated transformers in the bottleneck section of a segmentation network inspired by the U-Net. Liu et al. [22] utilize two networks for the segmentation: one for coarse segmentation and other for the refinement of the results from the first. Both networks are similar to the U-Net, but in the refine branch, a transformer is included. Its purpose is to provide features from global fields, compensating for the deep features that are used as input in this branch. In contrast, Zhang et al. [28] replaced the CNN encoder with a transformer encoder, exploiting its modeling capacity with self-attention.

The limitation of the input to the region within the retinal layer, ignoring what is outside of it, is seen in many of the multi-class papers [21, 25, 26, 27, 30, 31, 34], similarly to what was done in Pawan et al. [16]. There are various approaches for this delimitation, with some using CNNs trained for the segmentation of the retinal layers or the retina [31, 34], and others using algorithms leveraging on the noticeable transition between the retinal layers and its background [16, 21, 25, 26, 27, 30].

The retinal delimitation is conducted as a separate process from the fluid segmentation. In [21, 25, 26, 27, 30, 31], the retinal layer is segmented prior to the fluid segmentation, conditioning the input of the fluid segmentation network and simplifying the learning process. However, the retinal delimitation can also limit the final segmentation by intersecting the network's output, limiting the segmentation results to the boundaries of the retinal layer, as observed in Mantel et al. [34].

The fluid segmentation network input is conditioned in multiple ways. In Xing et al. [30], the image is cropped to fit its region of interest. [21, 26, 31] combined the B-scan with the retinal delimitation result, either through concatenation or along another channel. In [16, 25, 27] the information outside the retinal layer is set to zero and ignored.

Contrasting with the work of Liu et al. [17] who used a CNN to output a distance map (relative to the background or the retinal tissue), Tang et al. [31], and Rahil et al. [21], inspired by the work of Lu et al. [26], calculate a relative distance map to combine with the input slice in a CNN. Starting with the retinal delimitation, the relative distance to the internal limiting membrane (ILM) is calculated for each pixel located between the ILM and the Bruch's membrane (BM) (see Figure 1.2). This map provides information about the relative position of each pixel to the ILM, influencing their classification. An example of such framework can be seen in Figure 2.3.

Regarding the segmentation CNNs adopted by the analyzed papers, most are directly inspired by the U-Net, to which changes are done, when considering the objectives of each study. Examples of such changes are the introduction of blocks (such as residual [22, 25, 27, 28, 32, 34]), and modules (like atrous sampling pyramid pooling [25, 27, 29, 33]), which makes the network distinctive. However, some papers use other variations of the U-Net that are also popular: the Deeplab [36] in Li et al. [23] and Hassan et al. [27], and the VGG [37] in Hassan et al. [25] and Padilla-Pantoja et al. [32].

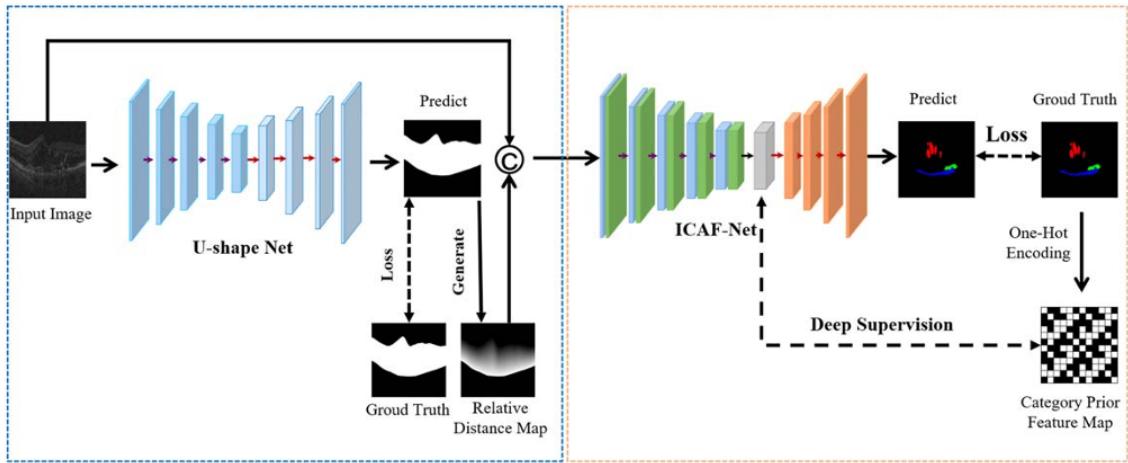


Figure 2.3: Example of a framework that includes delimitation of the retinal layer and a relative distance map (left side). The generated map is included in the segmentation network (denominated ICAF-Net, by the authors) [31].

2.2 Intermediate Slice Synthesis

For many years, there have been attempts to improve the resolution of OCT exams using computational methods, a process called super-resolution (SR). In 3D applications, such as magnetic resonance imaging (MRI), computed tomography (CT), and OCT, SR can be done intra-slice, which improves the resolution of each slice in the volume along one plane, or inter-slice, bettering the resolution of the volume along one axis, by generating one or more slices between a pair of original ones. Some frameworks may contain both approaches [38].

The use of GANs to generate slices between other known slices is commonly used technique in MRI and CT, but with few examples in OCT [38]. The systematic literature review performed by Ibrahim et al. [39], which analyzed the latest trends in the use of generative models in medical data, only presents one example of GAN for inter-slice resolution improvement in OCT volumes [13]. In this imaging technique, the use of GANs is mainly done for the generation of OCT images and conversion between different vendors [39].

In the following subsection, the state-of-the-art architectures used for the improvement of inter-slice resolution are presented.

2.2.1 Architectures

Given the lack of examples in OCT imaging, it was considered appropriate to study works from other imaging techniques, given that the working principle is the same across them. The selected papers can be classified into three distinct categories: inter-slice SR, which leverages information from adjacent slices to generate one or more intermediate slices [13, 40, 41, 42]; intra-slice SR combined with inter-slice SR, which improves the resolution of the slices from orthogonal planes and combines them with the results of inter-slice SR [43, 44, 45, 46]; and SR applied directly in 3D

volumes, utilizing three-dimensional convolutions in the generation process, which incorporates the information along all the axes from multiple slices simultaneously [47, 48, 49, 50].

In López-Varela et al. [13], present an inter-slice SR framework based on a GAN (inspired by the ResNet) for the generation of three B-scan slices between two known slices. The GAN training process, as illustrated in Figure 2.4, begins with the generation of an intermediate slice (Central Fake) located between two original B-scans (Pre and Post), which are separated by another original one (Central). The Central B-scan will serve as the ground truth (GT) and will be used for the assessment of image quality generated by the network. Subsequently, the network generates other two slices: one between the Pre and Central slices, designated as Pre-Central fake, and another between the Central and Post slices, named Post-Central fake. As the mentioned generations lack a corresponding GT, the network performance is regulated by using these two new synthetic slices to generate an additional Central Fake (Central Fake 2), which is then compared to the true Central. Consequently, if the generation of Pre- and Post-Central fakes are inadequate, the Central Fake 2 will also be of poor quality, resulting in a higher loss value. During the inference process, one slice is synthesized for every two known B-scans, reducing the inter-slice distance to half of the original value.

The importance of this study comes not only from it being the only study in OCT but also from the approach selected, which is similar to the foundation of the frameworks implemented in other papers.

In a more straightforward approach, Nishimoto et al. [42] utilize a baseline U-Net that uses two spaced slices as input to generate the slices between them. This methodology was tested in the generation of three, four, and five intermediate slices, and obtained better outcomes than those generated through linear interpolation.

The work by Xia et al. [40] demonstrates the enhancement of inter-slice resolution in MRI, through the utilization of multiple networks and a multi-scale discriminator that considers both the image from a large and a small field of view images. Additionally, the framework also estimates the depth and flow of each pair of images, generating an independent image from the GAN. This subsequently facilitates the generation of the intermediate slice.

Similarly, Wu et al. [41] improved the inter-slice resolution by training a single GAN to generate bi-directional spatial transformations instead of producing fake images. The advantage of this process is that it allows the same transformations to be applied to the segmentation masks from the surrounding slices, generating fake masks for the fake slices. As in Xia et al. [40], the discriminator also judges the generated images in both a larger and smaller field of view, but combines this with an object classifier that checks if the structures present in the neighboring slices appear in the fake one.

As an example of the use of intra-slice SR to improve inter-slice resolution, Zhang et al. [43] implemented two GANs that increase the resolution in the slices of the two planes with the lowest resolution of the volume (sagittal and coronal). In these planes, the dimensions of each slice are increased in the direction of the axis of lowest inter-slice resolution. Simultaneously, in the plane of highest resolution (axial), an architecture similar to López-Varela et al. [13] is used

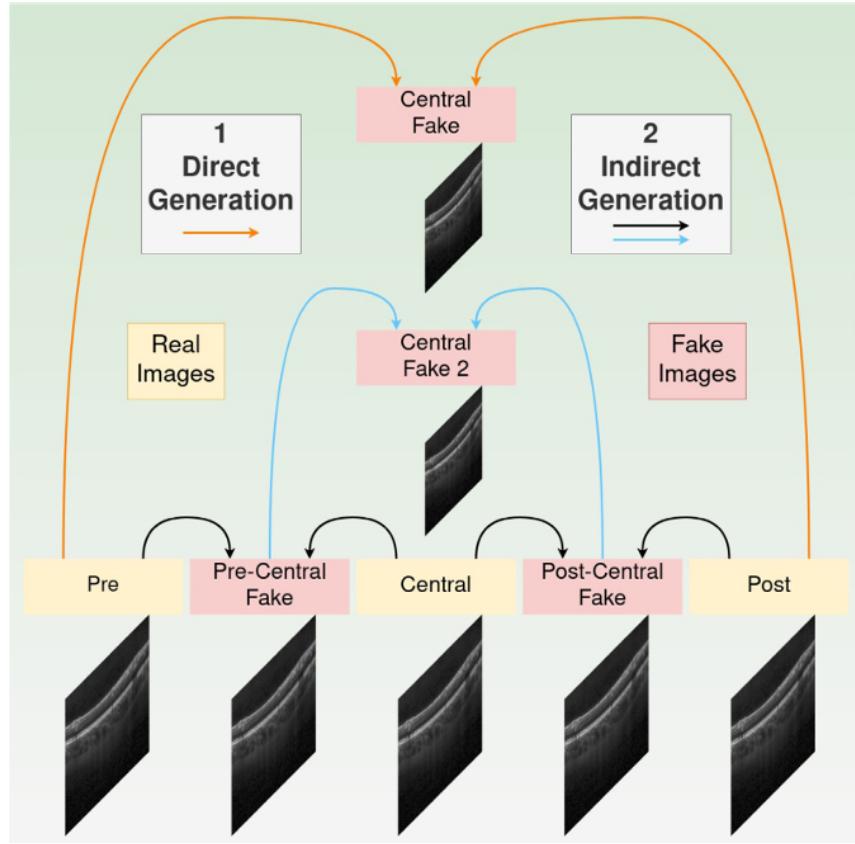


Figure 2.4: López-Varela et al. [13] training process.

in the generation of intermediate fake slices between each pair of known slices. The results from these three networks are then compared between each other, promoting the accurate and consistent generation of data among the networks.

A similar approach was done by Fang et al. [44], in which three networks (one for each axis) are trained to generate intermediate slices along one axis with a lower inter-slice resolution. However, during the unsupervised phase, upon each increase in resolution (a process that occurs twice), the information generated by the networks is compared between each other and a loss value that quantifies the performance is calculated, as illustrated in Figure 2.5.

Similarly, Nimitha and Ameer [45] use GANs to improve intra-slice resolution and a CNN to improve inter-slice resolution. The method starts by increasing the resolution of low-resolution (LR) slices, making them high-resolution (HR). Then an intermediate HR slice is generated between every set of two slices, using a CNN.

The same approach was also used by Georgescu et al. [46] to enhance the intra- and inter-slice resolution in CT and MRI scans. Two independently trained CNNs were used in LR volumes. One CNN was tasked with generating HR slices from the LR slices. Concurrently, the other CNN was utilized to reduce the distance between slices by increasing the resolution of the images from the orthogonal plane. By inferring an image with increased resolution along this plane, new intermediate slices were generated, improving the inter-slice resolution along the low resolution

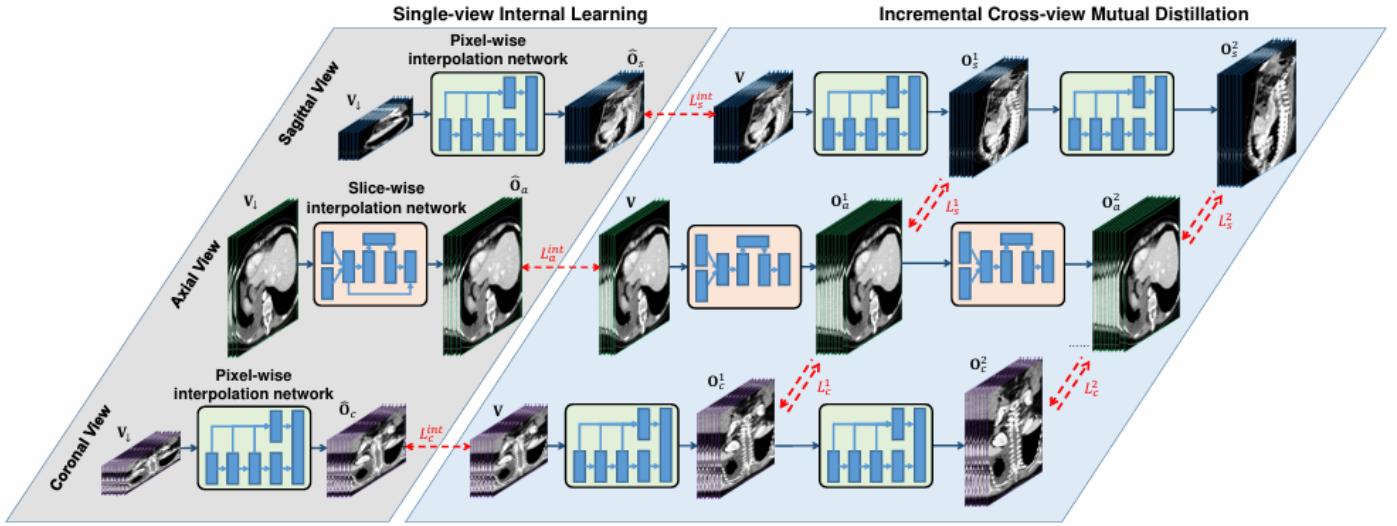


Figure 2.5: Pipeline of the methodology utilized by Fang *et al.*, 2022 [44].

axis.

The methodologies utilizing 3D GANs are similar between each other, as they all apply networks based on the GANs implemented in 2D images. As this method already considers the information across all the axes simultaneously, there is no need to use multiple networks for each, as seen in some of the previous approaches. Therefore, the differences between papers mainly originate from the medical imaging technique to which it is applied, the modules that constitute the 3D GANs used, and the datasets used for evaluation [47, 48, 49, 50].

Chapter 3

Methods

The Methods section starts with an overview of the dataset selected for the fluid segmentation and intermediate slice synthesis tasks, while regarding the requirements needed for the training of each model and the reasoning behind the selection. Afterwards, it provides an explanation of the experiments that will be done during the dissertation, regarding fluid segmentation, inter-slice generation, and fluid volume estimation, while explaining the methodologies that will be implemented.

3.1 Dataset

The application of deep learning to fluid segmentation in OCT volumes requires a large number of images annotated with the three retinal fluids for the training process. The manual segmentation of large amounts of B-scans is a laborious process, which results in a shortage of publicly available annotated OCT datasets. Consequently, the majority of these datasets contain a limited quantity of images.

The dataset selected for this dissertation is the RETOUCH dataset [51]. This dataset consists of 112 OCT volumes, obtained with four different devices: 38 from the Cirrus HD-OCT (Zeiss Meditec), 38 from the Spectralis (Heidelberg Engineering), and 36 from the T-1000/T-2000 (Topcon). The 112 volumes are split into training (70 volumes) and testing (42 volumes). Only those in the training set have annotations of the retinal fluids (IRF, SRF, and PED). For the training and testing of the segmentation models, only the annotated volumes will be used.

From the 70 volumes, 24 were obtained with the Cirrus, 24 volumes were acquired with the Spectralis, and 22 were obtained with the two Topcon devices. The number of B-scans per volume, the dimensions of the B-scans, and the axial resolutions vary according to the device utilized to obtain the OCT. The volumes acquired using the Cirrus have 128 B-scans, while those obtained with Spectralis have 49 B-scans. The volumes acquired using Topcon devices (T-2000 or T-1000) have 128 B-scans, but there are two volumes that only contain 64 B-scans. In total, 6838 B-scans will be used on the train and test of the segmentation model.

When compared with other renown OCT datasets annotated with retinal fluid, such as the Duke dataset [52], the two datasets from the University of Minnesota [53, 54], and the Lu et al. [26] dataset, the RETOUCH presents a significantly larger quantity of annotated volumes. It also shows more variety since the volumes were obtained using four different devices instead of including volumes from just one device, as done in the mentioned datasets. In Table 3.1, a comparison between the number of annotated B-scans in each of the mentioned datasets is shown, as well as the devices utilized to obtain the OCT images, the diseases of the patients, and the distribution of annotated B-scans per OCT volume.

Table 3.1: Volumes, B-scans per volume, the total number of B-scans, and macular diseases in each dataset

	DUKE2015 [52]	UMN2017 [53]	UMN2018 [54]	LU2019 [26]	RETOUCH [51]
Volumes	10	24	29	528	70 ^a
B-scans/Volume	11	25	25	Variable	128 (Cirrus and Topcon ^b), 64 (Topcon ^b), 49 (Spectralis)
B-scans	110	600	725	750	6838
Device	Spectralis	Spectralis	Spectralis	Spectralis	Cirrus, Topcon and Spectralis
Disease	DME	AMD	DME	DME	AMD and RVO

^a 24 volumes from Cirrus, 22 volumes from Topcon, and 24 volumes from Spectralis.

^b Two of the training volumes obtained using the Topcon devices have only 64 slices.

For these reasons, the RETOUCH dataset is regarded as a diverse and large dataset, widely used in the literature that aims to perform fluid segmentation using deep learning, as done in [21, 22, 23, 25, 26, 28, 30, 31]. These aspects motivated the selection of the RETOUCH as the dataset that will be used for implementing the models for fluid segmentation in OCT volumes in this dissertation.

In intermediate slice synthesis, the 112 OCT volumes that constitute the RETOUCH dataset will be used for the training and evaluation of the models. The volumes that do not have segmentation masks can also be included since these masks are not necessary in the intermediate slice generation task.

The consistent number of slices per volume and large quantity of OCT volumes make the RETOUCH dataset suitable for the training and evaluation of the models developed to generate intermediate slices.

3.2 Experiments

In this subsection, the experiments conducted during the dissertation are explained in depth. The subsection begins with a description of how the data was split, followed by the experiments in fluid segmentation and in fluid volume estimation.

3.2.1 Cross-validation

To promote consistency across all experiments, the conditions were held identical. In every experiment, the train-test split followed a 5-fold split. During training, all the images in three folds were

used in the training of the model, while the images from one fold was used in its validation. One fold was reserved and used to compare the performance between the best model from different experiments. Therefore, four training runs are completed in each experiment, rotating the validation fold across runs.

The images in the fold that was used in validation allowed an insight of how the model was learning. The instance of the model that achieved the lowest loss on validation data was saved, as this typically indicates the best generalization performance on unseen data. Also, when the model was no longer improving, training could be stopped, saving computational resources.

The dataset was split so that the quantity of each fluid per vendor and the number of volumes per vendor was equally distributed across the folds. By equally distributing the volumes, it is easier to assess the model's learning capability and its behavior towards data with different characteristics (e.g. data from different vendors). To accomplish a fair data split, a custom algorithm was elaborated. This algorithm sought to divide the data in five folds while minimizing the differences of fluid per vendor and the number of slices per vendor in each fold.

A possible distribution of 70 OCT volumes from the RETOUCH dataset, which were used in the training of fluid segmentation, can be seen in Table 3.2. The split was applied to the volumes and not to the slices. The slices of the same volumes must be kept together to prevent data leakage, where similar images, obtained from the same patient, are present both in training and validation, leading to over-optimistic performance metrics.

Table 3.2: Number of OCT volumes per vendor in each fold, considering 5-fold validation.

	1st	2nd	3rd	4th	5th
Cirrus	5	5	5	5	4
Spectralis	5	5	5	5	4
Topcon	$4^a + 1^b$	$4^a + 1^b$	4^a	4^a	4^a

Volumes marked with **a** consist of 128 B-scans.

Volumes marked with **b** consist of 64 B-scans.

In 3.2.2.2 Experiment 2, where the model performs binary segmentation of each fluid, the volumes can be redistributed using the same algorithm, with less bounds. In this experiment, it is relevant to split the volumes in folds based only on their vendors and quantity of the fluid to segment, thus eliminating the restrictions imposed by the quantity of other two fluids. Nevertheless, the volumes that are in the previously defined reserved fold can not be used nor in training nor in validation.

In the interslice generation experiments, the 5-fold split was not done by considering the fluids quantity in each fold. Since in this experiment the test volumes of the RETOUCH dataset were used and there are no fluid masks available, the quantity of fluid in each test volume is unknown. However, one of the folds in the interslice 5-fold split is the one reserved in the multi-class segmentation split.

The split was performed by taking into consideration solely the number of slices per device. In this experiments, the characteristic's of each device are important, since each device has a specific interslice distance, which is different even across devices of the same vendor and an important characteristic in generation.

Considering both training and testing volumes of the RETOUCH dataset, there are 38 Cirrus, 38 Spectralis, 13 Topcon T-1000 and 23 Topcon T-2000 (two of which with 64 slices). The fold reserved in the multi-class segmentation task is composed of the following volumes: 4 Cirrus, 5 Spectralis, 3 Topcon T-1000, and 2 Topcon T-2000 (one of which with 64 slices). The volumes remaining for the four folds used in the generation task can be distributed as in the Table 3.3.

Table 3.3: Number of OCT volumes per device in each fold, in the four remaining folds.

	1st	2nd	3rd	4th
Cirrus	9	9	8	8
Spectralis	9	8	8	8
T-1000	5	5	5	4
T-2000	3	2	2	2
T-2000^a	1	0	0	0

a: volumes with 64 B-scans.

Since the partition is not bounded by the quantity of fluid in each volume, it is possible to compute the best partition by iterating through all the possible combinations. In each combination, the standard deviation of the total number of B-scans in each fold is calculated. The combination with the smallest deviation was used.

Similar to what was done in the fluid segmentation task, three folds will be used in training while one will be used in validation. The reserved fold was used as a comparison between the best generative models from different experiments.

3.2.2 Fluid Segmentation

The initial experiments of this dissertation focused on training networks on the fluid segmentation task. The goal of these experiments is to determine which segmentation network performs the best in the considered task, which were later required for the fluid volume estimation.

In these experiments, the U-Net [35] was used in the multi-class segmentation of the fluid regions in each B-scan. The U-Net is distinguished by its encoder-decoder structure, which resembles the letter U (see Figure 3.1). In the encoder path, two 3x3 unpadded convolutions are applied to the input image, with each being followed by a rectified linear unit (ReLU) and a 2x2 max pooling operation with a stride of 2, downsampling the image. In each downsampling step, the number of channels is doubled. In the expanding path, a 2x2 up-convolution is used, resulting in the halving of the number of channels. The result is then concatenated with the cropped feature map from the respective contracting path. A 1x1 convolution is applied to the final layer.

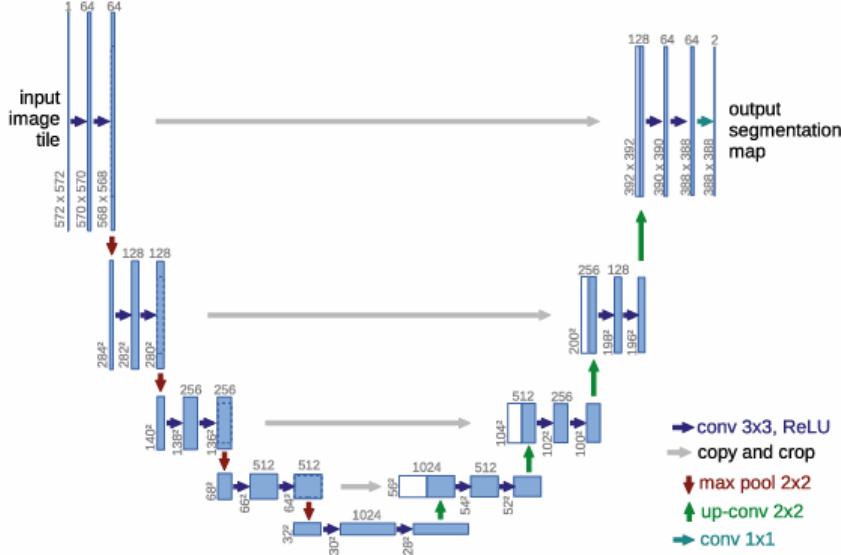


Figure 3.1: U-Net architecture [35].

The evaluation of all networks will be conducted using the Dice coefficient. The Dice coefficient is a commonly used metric for evaluating the similarity between two sets. In this context, it will be used for assessing the similarity between the segmentation mask generated by the segmentation network and the GT. The equation that describes the Dice coefficient can be seen in Equation 3.1, where A is a set that represents the GT binary mask of one fluid and B is another set that represents the predicted binary mask of the same fluid [55]. Considering a_i and b_i the binary pixels, the Dice coefficient can be rewritten as shown in Equation 3.2. The network that performs the best will be selected to estimate the fluid volumes in the fluid volume estimation experiments.

$$\text{Dice}(A, B) = \frac{2|A \cap B|}{|A| + |B|} \quad (3.1)$$

$$\text{Dice}(A, B) = \frac{2 \sum_i a_i b_i}{\sum_i a_i + \sum_i b_i} \quad (3.2)$$

The loss function that regularized the training in the fluid segmentation experiments was the same as the one used in Tennakoon et al. [56], whose segmentation model was previously implemented by the authors. This loss is described as seen in Equation 3.3, where λ_D is the weight of the Dice component, \mathcal{L}_D , and λ_{CE} is the weight of the cross-entropy component \mathcal{L}_{CE} , with both weights being 0.5.

$$\mathcal{L} = \lambda_D \mathcal{L}_D + \lambda_{CE} \mathcal{L}_{CE} \quad (3.3)$$

The component \mathcal{L}_D is the Dice loss of the foreground. This translates to how good the model is at detecting and segmenting the fluid present in the B-scans. For any image, where each pixel is associated with an index j , the loss can be described through Equation 3.4, where s_{j0} is a binary variable that is 0 when the pixel j belongs to the class 0 (background) and is 1 whenever the pixel

j belongs to any class that is not 0 (foreground). $p_{j\bar{0}}$ corresponds to the predicted probability of the pixel j belonging to the foreground. The ϵ constant is a small value utilized to prevent division by zero.

$$\mathcal{L}_D = 1 - \left(\frac{2 \sum_j s_{j\bar{0}} p_{j\bar{0}}}{\sum_j s_{j\bar{0}} + \sum_j p_{j\bar{0}} + \epsilon} \right) \quad (3.4)$$

However, this loss component is not enough to correctly label the pixels in their respective classes and, for that reason, the cross-entropy component was used. Due to the large class imbalance in the images, with the background occupying the majority of them, the cross-entropy is balanced by taking into account the number of pixels belonging to each class. The cross-entropy is calculated for each pixel of index j belonging to the image. Then, for each class, the cross-entropy of all pixels in the image is summed, before being divided by the number of pixels that belong to the class. The mean of the values obtained for each class result finally in \mathcal{L}_{CE} , as can be seen in Equation 3.5.

$$\mathcal{L}_{CE} = - \sum_{c \in C} \frac{1}{4} \left(\frac{1}{\sum_j s_{j,c}} \sum_j s_{j,c} \ln p_{j,c} \right) \quad (3.5)$$

3.2.2.1 Experiment 1

In the first experiment, the base U-Net model was trained to perform 2D multi-class segmentation of the retinal fluids in OCT volumes.

This was the most extensive experiments, where many variables were tested. Different patch shapes, transformations, and hyperparameters were experimented, until the best training settings were determined. The best settings were then used in 3.2.2.2 Experiment 2. All the experiments were done using the Adam optimizer [57] with a learning rate of 2×10^{-5} .

Experiment 1.1 The model was initially trained on patches of size 256×128 ($H \times W$), following the same implementation as the one in Tennakoon et al. [56]. The extraction of patches aims at prioritizing the B-scan information relevant for the segmentation. To achieve this, the patches are not distributed uniformly. Instead, 10 patches are extracted from a random location inside the region of interest (ROI) of each image. The image's ROI is the part of the image where the entropy is above a determined threshold or where there retinal fluid is present. The patches are then augmented by a rotation between 0 and 10 degrees, and horizontal flipping. Of the patches with no fluid, 75% of them were dropped. In Figure 3.2, it is possible to see the overlaying of the fluid masks and the ROI, with a red bounding box signing a patch that would be used as input to train the U-Net.

In the Experiment 1.1, two sets of four training runs were performed, using each fold as validation. In both sets, the conditions were exactly the same, except the input patches. This experiment aimed to understand the effect that the random patch extraction has on the model performances.

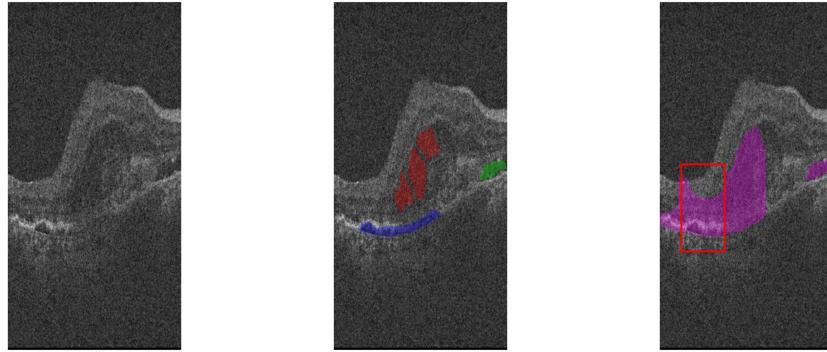


Figure 3.2: Cirrus B-scan (left), fluid masks overlay (middle) with IRF in red, SRF in green, and PED in blue, and the ROI mask overlaid in purple (right). The red bounding box signals a possible 256×128 patch that could be extracted.

Experiment 1.2 In Experiment 1.2, the patch shape was changed from 256×128 to 496×512 . By using such shape, the model receives a larger context of the B-scan as input, allowing it to learn the anatomic references that characterize and limit the fluids.

The patches used in this experiment were no longer randomly extracted from the ROI. Instead, the patches were extracted from top to bottom so that every section of the image would be present in at least one patch. In a Cirrus B-scan, with shape 1024×512 , the first patch would correspond to section from $y = 528$ to $y = 1024$, while the second patch would be from $y = 32$ to $y = 528$. The last patch would then start on the bottom of the image, at $y = 0$, to $y = 496$. A representation of this process can be seen in Figure 3.3. The patches are extracted from top to bottom so that the retina and the fluid would not be split in two patches, damaging the quality of the input data.

In this experiment, due to the larger size of the patches that are being loaded, the batch size had to be reduced from the usual 32 to 16. It was trained on 100 epochs with the same transformations as in the previous experiment.

Experiment 1.3 Another patch shape was experimented in Experiment 1.3. In this experiment, the images from different vendors were resized from their original dimensions to 496×512 , the shape of the smaller images of the dataset, obtained with the Spectralis device.

The dimensions of the voxels in the OCT volumes change according to the device that was utilized to obtain the volume, resulting in images with different appearances across the vendors. For example, each voxel in the Cirrus volumes has an height of $1.95 \mu\text{m}$, while each voxel in the Spectralis volumes has an height of $3.87 \mu\text{m}$. For the same image, these differences in height lead to the same structures appearing bigger in Cirrus B-scans (see Figure 3.4). These differences across vendors makes the learning of the segmentation harder. Therefore, by resizing all the images to the same shape, the structures will have more consistent dimensions across vendors and the voxels will roughly translate to the same dimensions, leading to a easier learning process for the model.

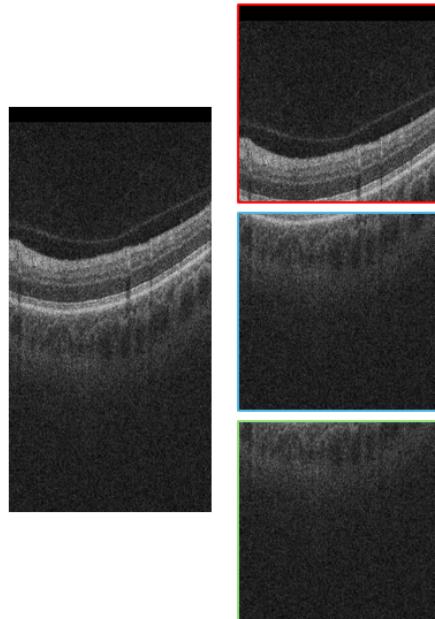


Figure 3.3: Cirrus B-scan and its respective three patches of shape 496×512 .

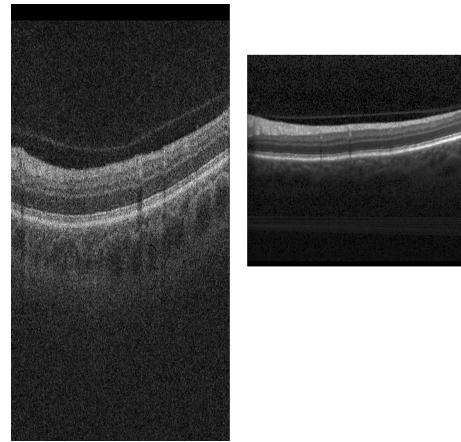


Figure 3.4: B-scan of the retinal layers in different patients, using Cirrus (left) and Spectralis (right) devices. In Cirrus, the retinal layers appear much larger than in Spectralis.

Then, vertical patches, of shape 496×128 , were extracted from each B-scan. The number of patches extracted from each image was changed, experimenting with four (Figure 3.5), seven (Figure 3.6) and thirteen (Figure 3.7) patches. The advantage of extracting vertical patches is that each image contains both the complete retinal layer and the background. This does not happen in the previous experiments, where the patches are either too small to contain both background and the retinal layers (in Experiment 1.1) or the retinal layers are cropped during patch extraction (in Experiment 1.2, as seen in Figure 3.3).

The number of patches that performed best was then experimented with three different rotations: no rotation, maximum rotation of 5° , and maximum rotation of 10° . These values were tested for a better understanding of how the rotation of the image affects the segmentation and the

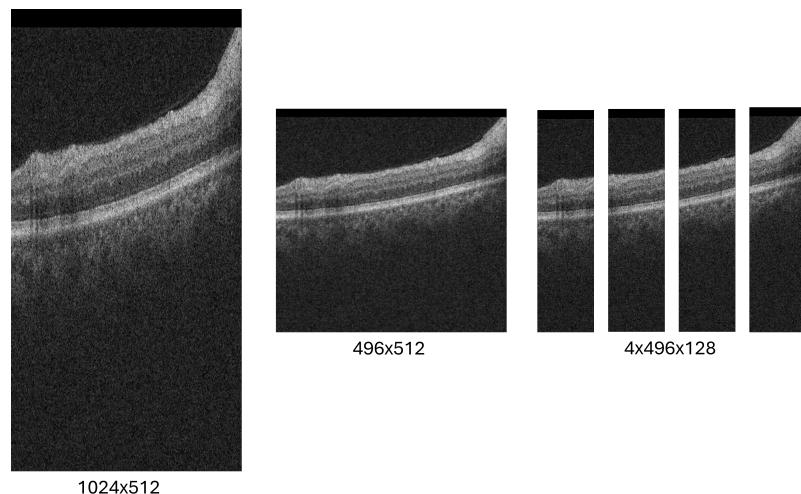


Figure 3.5: Four vertical patches of shape 496×128 extracted from a Cirrus B-scan.

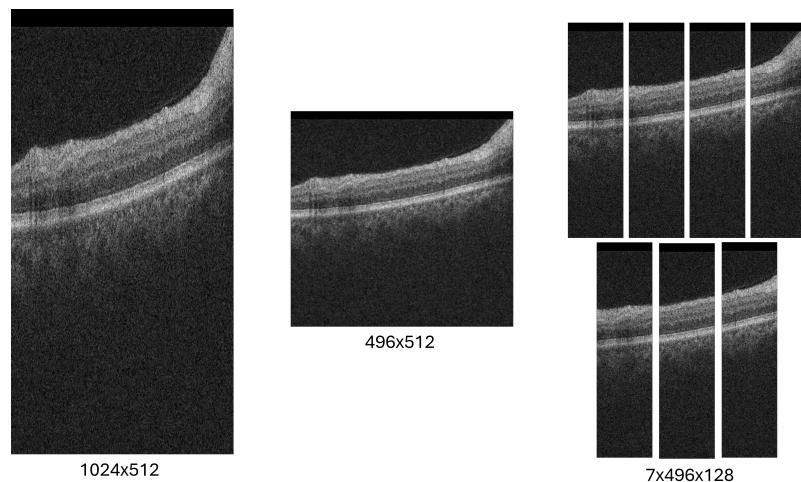


Figure 3.6: Seven vertical patches of shape 496×128 extracted from a Cirrus B-scan.

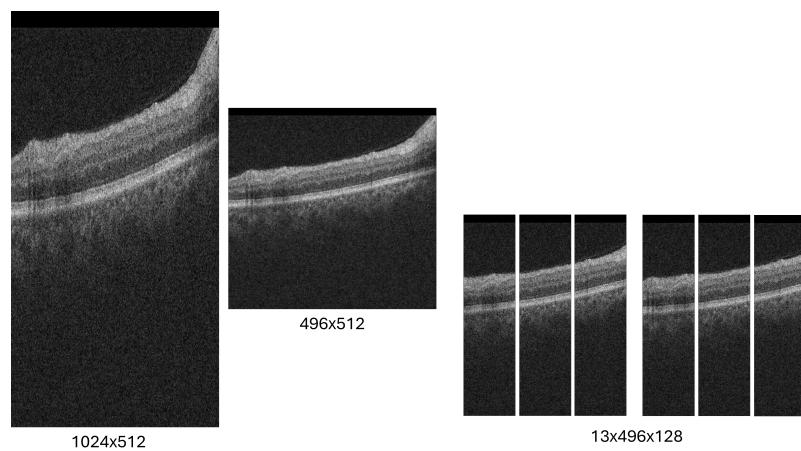


Figure 3.7: Thirteen vertical patches of shape 496×128 extracted from a Cirrus B-scan.

model's understanding of anatomic references.

3.2.2.2 Experiment 2

The second experiment also involved multi-class segmentation of the retinal fluids. Contrasting with the first experiment, where the segmentation was done using a U-Net, in this experiment three U-Nets were used, one for each fluid. Each U-Net model focus only on the segmentation of one fluid, with one model for IRF, one for SRF, and one for PED.

One of the main problems with multi-class segmentation performed by binary models is the merging of the multiple masks. In this context, multiple fluid classes can be predicted for the same voxel, while only one of those can be correct. In this experiment, two alternatives were explored: order of priority, where the merging of the fluid masks follows a predefined hierarchy that determines which fluid takes precedence, and highest probability, where the assigned class is the one that was predicted with highest probability by its model.

Two different losses were used to regulate the model. Initially, the same loss as the one used in 3.2.2.1 Experiment 1, with only two classes (background and the fluid that would be segmented), and then, the weighted cross-entropy, using weights that balance the larger quantity of background voxels.

3.2.3 Intermediate Slice Synthesis

The objective of the subsequent experiments is to improve the resolution between slices, thus approximating the fluid volume that will be estimated to the true value.

The intermediate slices will be generated using the RETOUCH dataset. In this experiment, subvolumes that consist of overlapping triplets of consecutive slices, sampled with a step size of 1, will be used, as shown in Figure 3.8. The first and the last slice of these triplets will be used for the generation of the middle slice. Consequently, it is possible to evaluate the generated slice in comparison to the original one, as done in other examples of the literature. For each volume, the number of potential subsets is then determined to be $n - 2$, where n represents the number of slices within the same volume.

The generation of slices can be evaluated in specific metrics, as well as through qualitative assessment. To assess the efficacy of the generation model, the model utilized for fluid segmentation could be used for the estimation of the fluid's area in the generated image and to compare the resulting mask with the original image's mask. This comparison can be conducted using the Dice coefficient [13] (see Equation 3.2). However, this metric is insufficient for evaluating the generation performance, as it requires comparisons that encompass the entire slice and not just the fluid. Examples of such metrics include the mean absolute error (MAE) [13, 41, 50], the peak signal-to-noise ratio (PSNR) [38, 40, 43, 44, 45, 47, 48, 49, 50], and the structural similarity index measure (SSIM) [38, 43, 44, 45, 47, 48, 49, 50].

The MAE and MSE quantify the errors between the original image and the generated image. For every pixel, the difference between the value in the original image and the generated image is

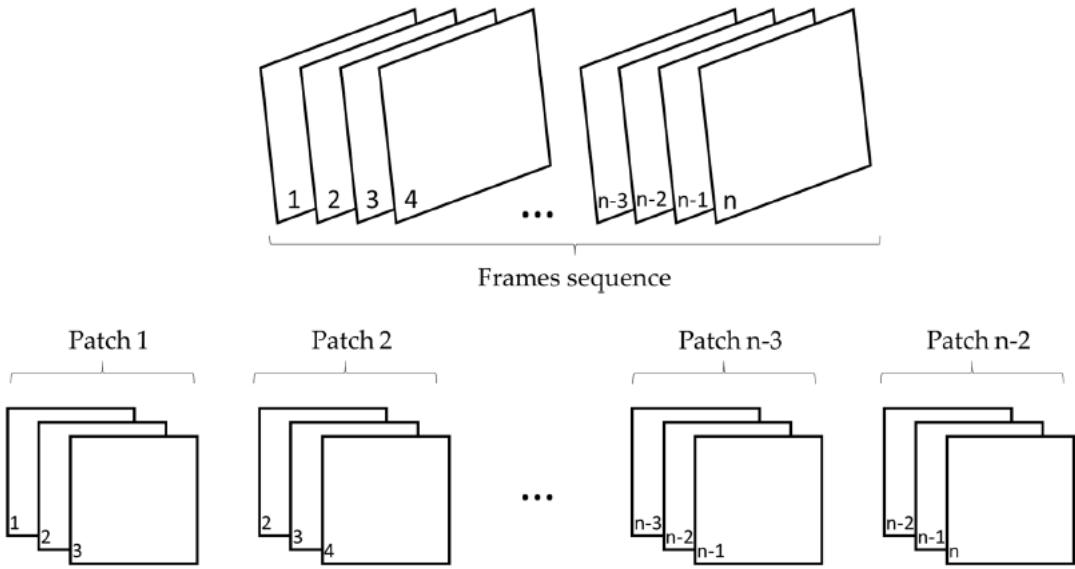


Figure 3.8: Scheme explaining the input data of the generative models. Each frame refers to B-scan from an OCT volume. Extracted from Tran and Yang [58].

calculated. In MAE, the absolute value of this difference is calculated, and then the mean of all pixels in the image is computed. Meanwhile, in MSE, the difference is squared before computing the mean. In Equation 3.6 and Equation 3.7, MAE and MSE are described, respectively, where x_i is the intensity of the pixel of index i in the predicted image, while y_i is the intensity of the pixel with index i in the original image [59, 60].

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^N |x_i - y_i| \quad (3.6)$$

$$\text{MSE} = \frac{1}{N} \sum_{i=1}^N (x_i - y_i)^2 \quad (3.7)$$

PSNR is a metric used to calculate the ratio between the maximum signal power (which corresponds to the maximum value of a pixel in the image) and the power of the distorting noise, which affects the quality of its representation. Therefore, the PSNR, described in Equation 3.8, is inversely proportional to the mean squared error. PSNR can also be understood as the representation of absolute error in dB [59]. It is important to note that in OCT the signal-to-noise ratio is low, due to the speckle present in the images. Therefore, a smaller PSNR is also expected, when compared with other imaging techniques that do not present as much speckle [2].

$$\text{PSNR} = 10 \cdot \log_{10} \left(\frac{L^2}{\text{MSE}} \right) \quad (3.8)$$

While the previous metrics focus on the differences between two images at a pixel level, the SSIM is based on the perception of the image. This metric considers the change of perception

in structural information, estimating the perceived quality of images and videos. SSIM measures the similarity between the original image and the generated. The SSIM is calculated as shown in Equation 3.9, where x and y represent the generated and the original images, respectively, so that μ_x and μ_y are their local means, σ_x and σ_y are their standard deviations, while C_1 and C_2 are small constants that stabilize the division [59].

$$\text{SSIM}(x, y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)} \quad (3.9)$$

Since the best performing models in segmentation resized the images to 496×512 , the images were generated to match those dimensions. Therefore, regardless of the device utilized to obtain the OCT volume, all its B-scans were resized to 496×512 for both experiments of image generation.

Experiment 3 In the first experiment focused on intermediate slice synthesis, a GAN will be used. The underlying principle of a GAN, originally proposed by Goodfellow et al. [61], is based on a competitive game between two networks. The generator network starts with the first and last slice of a subvolume, which is composed of three consecutive B-scans from an OCT scan, and aims to generate the intermediate slice. In contrast, the discriminator network is trained to distinguish between the generated and real slices. When the discriminator correctly labels generated slices as fake, the generator will be penalized, motivating it to fool the discriminator and consequently improving its generation, resulting in outputs more similar to the real inputs. However, the discriminator network loss also penalizes misclassifications, dependent on the probability of the prediction. As a result, as the generator improves, so does the discriminator [62]. The overall framework for GANs is illustrated in Figure 3.9.

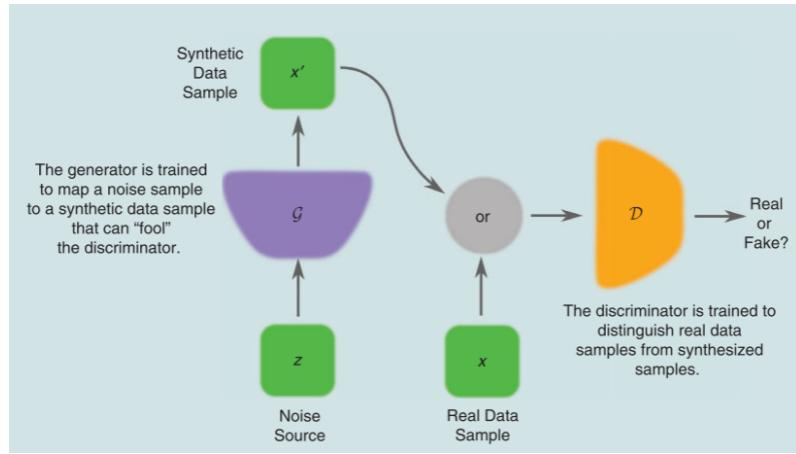


Figure 3.9: Example of a GAN framework, where \mathcal{D} is the discriminator and \mathcal{G} is the generator [63].

The GAN implemented by Tran and Yang [58] was used to generate the intermediate slices of the OCT volumes. This framework is used in the interpolation of intermediate slices in video and is trained in patches of 64×64 .

In the original implementation, one patch is randomly extracted from the triplet of images and used in training. Due to the much smaller quantity of data available in OCT, from each triplet of scans, all the possible disjoint 64×64 patches were extracted. The extraction was done from top to bottom and in the last row of slices, the image was padded until it had 64 pixels. An example of the patches extracted from a Cirrus B-scan can be seen in Figure 3.10.

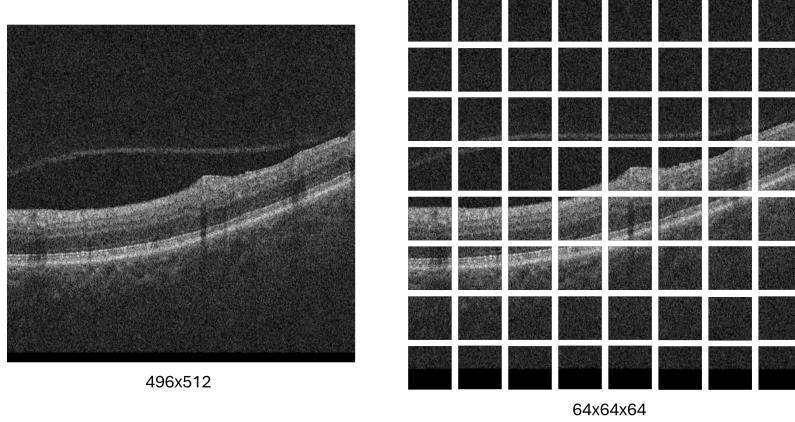


Figure 3.10: Patches with shape 64×64 extracted from a Cirrus B-scan which was resized to 496×512 .

Experiment 4 As in the previous experiment, the intermediate slice will be generated using the first and last slices of a subvolume that consists of three consecutive B-scans from an OCT scan. However, in this experiment, inspired by the work of Nishimoto et al. [42], the intermediate slice will be generated using a U-Net. While the U-Net is more commonly applied in segmentation, as seen in the reviewed literature, Nishimoto et al. [42] apply it to generate the intermediate slices of a subvolume. The U-Net receives the edge slices as input and forces the output of the intermediate ones. In the paper [42], this was tested for three, four, and five slices. However, in this experiment it will be utilized to generate a single intermediate slice.

3.2.4 Fluid Volume Estimation

The estimation of fluid volume will be done once the optimal segmentation and intermediate slice generation models have been selected. Afterwards, the intermediate slice generation model will synthesize slices in the OCT volumes. The segmentation model will then be applied to both the unaltered volumes and the volumes with generated slices.

The area of each fluid in each OCT scan will be estimated considering the resolution of each OCT scan, which varies according to the device utilized to obtain the OCT volume. Afterwards, the area will be multiplied by the axial distance (half the axial distance to the previous slice plus half the axial distance to the following slice) to obtain the volume of fluid per slice. In the first and last slice of an OCT volume, the area will be multiplied by half of the axial distance (half the axial distance to the neighboring slice). The total volume of fluid in an OCT scan can be estimated by

summing the fluid volumes of all individual B-scans. This allows the volume estimation of IRF, SRF, and PED, as well as the overall fluid volume in the OCT scan.

Experiment 5 In this experiment, the fluid volumes will be calculated for the OCT scans without the generated slices. The best segmentation model will segment the fluid in three classes and the volume will be estimated for each class as described. The results from this experiment will allow the comparison with the values obtained in the following experiment, where slice generation will be used.

Experiment 6 This experiment will consist of the fluid volume estimation in OCT scans with generated images. Similar to the previous experiment, the best segmentation model will predict the fluid masks and the fluid volume will be estimated. The values obtained will be compared with those calculated in the previous experiment. It is expected that the volumes will not vary more than one order of magnitude between experiments. In case a significant difference is observed, the generated images and their respective masks must be analyzed.

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Appendix A

Lorem Ipsum