rPPG for automatic EMR generation in the Care2Report project

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Assignment H

Notice of Originality
I declare that this paper is my own work and that information derived from published or unpublished work of others has been acknowledged in the text and has been explicitly referred to in the list of references. All citations are in the text between quotation marks (“ ”). I am fully aware that violation of these rules can have severe consequences for my study at Utrecht University.

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1 Introduction

Care2Report is a research program with the goal of automating the generation of medical recordings through the use of audio, video and sensor inputs (Maas et al., 2020). The process consists of three stages: recording, interpretation, and report generation. Research is in its early stages, but the first experiments have been already carried out with the first prototype mostly composed of off-the-shelves technologies, showing promising results. The main drive behind this research is the incredible investment necessary to generate Electronic Medical Records (EMR).

An EMR is a digital record of the medical history of a patient, it facilitates tracking and improves communication of patient information between institutions and healthcare professionals. Research carried out on its benefits by Campanella et al. (2016) showed a 22.4% reduction in documentation time, higher guideline adherence and a lower number of medication errors. These benefits however are offset by the large time, and therefore money, investment necessary to produce these records.

In a paper by Chaiyacha et al. (2019) it was reported that, within a 24-hour period, interns in the United States spent on average 10.3 hours solely interacting with the EMRs. This accounted for 43% of their time while educational activities and direct patient care amounted to just 20% of their day. Furthermore, research into the topic by Woolhandler et al. (2003) showed that administrative costs in the United States amount to an estimated 15.5 billion dollars, an average of 13.5% of a physician's time. Facilitating the generation of EMRs through the Care2Report research could therefore help reduce spending and ease administrative burdens for health practitioners.

As previously mentioned, the Care2Report functional architecture is composed of three phases, with the first one involved in recording video, audio and sensor input. In this paper, the focus will be on sensor input gathering for the Recording phase through the remote photo-plethysmographic imaging (rPPG) technique in ambient light conditions and in particular on the paper "Remote plethysmographic imaging using ambient light" by Verkruysse et al. (2008).

The PPG technique detects cardio-vascular pulse waves by observing variations in light reflectance caused by blood flow. These variations can in turn be used to measure vital signs such as heart and respiration rates, blood pressure and more. While commonly contact probes are used, rPPG instead achieves these results at a distance through the use of cameras.

The creation of the original non-remote PPG technique dates back to 1937, with a paper by Hertzman and Spealman (1937), while the first attempt at remote PPG is far more recent, as described in a paper by Wieringa, Frits, and van der Steen from 2005 (Wieringa et al., 2005). For more information regarding the history of the technique, please see section 3. The Care2Report project is backed by a large team, nevertheless the writers of the Care2Report paper are Maas, Geurtsen, Nouwt, Schouten, Water, Dulmen, Dalpiaz, Deemter, and Brinkkemper (Maas et al., 2020).

In the next section, a hypothetical examination will be described in accordance with the procedure described by a more recent rPPG paper by van der

Kooij and Naber (2019), compatible with the principles of the Care2Report paper, and inspired by the Video2Report database (Schiphorst et al., 2020), which was created as part of the Care2Report project. In section 3, the focus will be on the original experiment, the history of the technique, and further research done with different types of cameras, illumination, and procedures.

2 Example

The example takes place in a hospital room, where a doctor conducts an examination to determine the heart rate (HR) of the patient.

2.1 Materials and environment

Other than a normally furnished hospital room, an inexpensive switched-off camera is set up on a tripod, to be pointed towards the face of the patient. Illumination is provided by daylight and artificial fluorescent light.

This setup respects principle 1 of the Care2Report system, as there is minimal interference with a normal hospital environment.

It is important to note that illumination and camera type might affect the results of the test, but the effectiveness of the technique has already been demonstrated in similar conditions as the ones described (Verkruysse et al., 2008).

2.2 Examination

The examination is divided into two subsections, one on the doctor and patient's side, and one on the side of the Care2Report software.

2.2.1 Doctor and patient

The doctor enters the room, informs the patient of the procedure, obtains consent, and then turns on the camera, receiving an audio confirmation that the recording and processing have started. The doctor then proceeds to determine the HR of the patient through a contact PPG while the system processes in real-time the HR of the patient through rPPG. After 30 seconds the procedure is complete, the doctor stops the recording and prepares to check the report generated.

2.2.2 Care2Report software

During the procedure, on the system's side, each frame of the video is processed to obtain the HR by the rPPG software. The steps, taken from the paper by van der Kooij and Naber, are: "(i) spatiotemporal cropping of videos, (ii) facial skin selection, (iii) averaging and filtering signals, (iv) independent component analysis, (v) fast Fourier transform, (vi) filtering power spectra, and (vii) respiration/movement signal rejection" (van der Kooij & Naber, 2019, p.5). In the following steps all the values will be taken from the original paper except for the resulting HR:

In the first step, the input video is cropped in space and time, removing irrelevant background objects of the hospital room and cropping the first and last three seconds of the video where the patient moves in anticipation of the beginning and ending on the examination. The video is cropped around the patient's face thanks to automatic facial tracking.

In the second step, the skin color of the patient is automatically detected and isolated in the image through a 4-means clustering approach, according to squared Euclidean distance and with a maximum of 100 iterations, filtering unnecessary features of the face.

In the third step, each video frame is averaged per RGB channel, transformed into a function of time, and filtered with a sixth-order Butterworth filter with a cutoff frequency of 0.04Hz. The filtered signals are then subtracted again to their original signal in function of time, obtaining new filtered signals.

In the fourth step, three components are computed from the signals through Independent Component Analysis with 2000 iterations and stabilization on as parameters.

In the fifth step, the component signals are fast Fourier transformed resulting in power spectra.

In the sixth step, the power spectra are filtered with a zero-phase third-order low-pass Butterworth frequency filter, with a cutoff frequency of 0.2Hz.

In the seventh step, through the respiration rejection rule, power peaks corresponding to the HR are chosen, and the final average HR of 90 is computed.

At the same time the remaining Care2Report software processes all other inputs necessary in order to generate the information necessary for the report.

This examination respects principles 2 and 3 of the Care2Report system, as the sensor is easily activated and generates data in real-time.

2.3 Report

The Care2Report software proceeds to interpret all the data obtained at the previous step, to be further processed and finally transformed into the report. These two steps are complex, deserving their own papers to be properly explained, and therefore their inner workings will not be described here and it will be assumed that the Care2Report system takes care of the interpretation of data and generation of the report.

The doctor reads through the summary of the consultation, cross-references the HR measured with the one written in the automatically generated report, confirms that the report is correct, and then uploads it to the EMR. The report generation system adds information regarding the correct generation of the report to its own database. Data recorded for the generation of the report is then discarded, and the process is now complete.

The report should recite "Examination of patient Giacomo Fiorentini. Heart rate 90." with more data for every medical activity performed and for every scheduled future activity (e.g. Confirmed new examination next week), with the possibility to edit them if incorrect. The report is ultimately a summary of the consultation, presenting all important information and steps that occurred.

This step respects the principles 4, 5, 6, and 8 of the Care2Report system, as the report is a concise summary, checked and possibly corrected by the care provider, while the system learns from having correctly generated the report and then discards data according to the principles of General Data Protection Regulation (GDPR).

3 rPPG and Related Literature

While this example treats both PPG and rPPG as mature technologies that can be easily integrated within a larger system, it is worth contextualizing the two technologies within their history and the current period. The history of PPG starts in the 1930s in a paper by Hertzman and Spealman (1937), who discovered a simple and cheap method to detect circulatory changes in an area of the skin through the use of light source such as "a pencil flashlight bulb" (Hertzman, 1938, p.1).

Regarding rPPG instead, while it was first demonstrated in the paper by Wieringa et al. (2005), it only truly garnered attention after the paper by

Verkruysse et al. (2008) recorded accurate HR and respiratory rate (RR) data through the use of a consumer-grade camera in ambient light. The paper, in particular, reaches three important conclusions: the visible wavelength of light, including not only green but also red and blue light, can be used for rPPG in ambient light conditions; at distances of up to 11m (with the application of a 2x telelens); and with the use consumer-grade cameras.

Let us now contextualize the rPPG paper by comparing its experiment with two other papers published in similar years by Zheng et al. (2008) and Humphreys et al. (2007), and the paper that first demonstrated this technique by Wieringa et al. (2005). The three areas of comparison will be the light wavelength used, the cameras used and the distance between the camera and the subject. As can be seen in the table 1, the experiment was innovative both for the distance, the use of visible light and the type of camera involved.

	Verkuysse et al.	Wieringa et al.	Humphreys et al.	Zheng et al.
Light	Visible light	Infrared	Infrared	Infrared
Camera	Consumer grade	Custom camera	Custom camera	Custom camera
Distance	150cm	72cm	30cm	5cm

Table 1: Experiment comparison

Another research paper of interest by van der Kooij and Naber (2019), was written with the goal of offering publicly available software implementing the processing steps to extrapolate HR from a recorded video. Furthermore, the steps described in this paper were used to model the behaviour of the system in the aforementioned example, as they were both more modern than the original rPPG's implementation, adding steps such as automatic face detection, and designed to standardize future tests.

Another paper that guided the creation of the example was Video2Report (Schiphors et al., 2020), as it was the only available example of a recording that was developed as part of the Care2Report project. The aim of the paper was to create a publicly available database for automatic recognition of medical actions, but the conditions in which the videos were recorded would also fit the requirements necessary for rPPG if the face of the patients were visible in the recording. It was therefore fundamental in order to visualize the scenarios in which the rPPG technique would be implemented.

4 Additional Findings

Due to the lack of open-source and accessible code and the rather niche scope of the technique itself, it should not come as a surprise that most of the literature written on the topic is found in scientific papers. The barrier of entry for a basic implementation is very high. Despite this, youtube.com proved to be a valuable source, containing videos of various nature, ranging from more academic presentations to homemade experiments, dating all the way back to 2013. This section contains a review of these videos and the review of a patent for an rPPG technique.

The presentation by Amogh Gudi (nomadx, 2013) represents, to the best of this author's knowledge, the first mention of rPPG on youtube. The general implementation approximately follows the aforementioned technique, but two details are of particular interest. The first one is an observation on the red colour channel which they define as noisy in detecting HR, and mention the possibility of it containing mostly RR data. The removal of the red channel might therefore help reduce the number of power peaks associated with the RR for the "respiration/movement signal rejection" step of the rPPG technique in the paper by Kooij and Naber (2019). Secondly, another interesting aspect is their version of this very step which includes: a filter with a dynamic threshold, and a first and second-order slope detection to filter out smaller and flatter peaks that do not represent the heartbeat. This approach is rather different from the one described by Kooij and Naber (2019) and might be useful in developing a more general version of the step that works with all types of datasets.

Another interesting contribution comes from a single author publishing multiple videos showing implementations of techniques from some of the papers they wrote. The six videos (Wenjin Wang - computer vision for healthcare, 2015a, 2015b, 2015c, 2017, 2018, 2019) show different techniques built with different purposes and strengths, such as being motion-robust, privacy-preserving, or simply a new way to detect HR from an image. The videos provide a brief explanation of the algorithms, examples of the technique in use, and sometimes MATLAB code snippets. In the context of the Care2Report project, many of these techniques could fit the role of rPPG detection in place of the core technique described in this paper.

The same author is also responsible for the patent "Device, system and method for determining a physiological parameter of a subject" (Wang et al., 2020). This patent covers a wide variety of possible techniques, citing many different approaches to many of the steps of rPPG. The most interesting and novel approach part of this patent is found in the selection of the region of interest (ROI). The proposed method consists of using various techniques and metrics to generate multiple weight maps of each frame. These weight maps could then be picked and combined, according to statistical parameters of the maps themselves such as mean, standard deviation, and variance, in order to replace ROI detection and ROI motion tracking.

Another meaningful contribution to the field of rPPG comes from Phillip Rouast (2016a). It is, to the best of this author's knowledge, the first example of an open-source rPPG method on youtube.com and possibly one of the first open-source implementations overall. The program is rather lightweight as it runs both on a desktop and a mobile phone, tracks the ROI automatically, works at a rather low framerate of approximately 10, and obtains signals correlated to the HR as can be seen in the second half of the video where, after exercising, the detected HR increases. For a more rigorous example of this software's use, the same author also performed the experiment in a laboratory with a PPG and electrocardiogram baseline to compare the detected HR to (Phillip Rouast, 2016b). In any case, minimal movement and good lightning are present in both videos, allowing the rPPG signals to be obtained in almost optimal conditions.

The final video covered is an oral presentation of the paper "Siamese-rPPG Network: Remote Photoplethysmography Signal Estimation from Face Videos" (李翊安, 2020). The proposed technique uses deep learning in order to predict HR from a video, and is composed of three steps: ROI detection, Analysis through a Siamese Neural Network with 3D convolutional layers, and rPPG signal summation. A Siamese Neural Network is a neural network model with two branches with equivalent layer weights which process two inputs in parallel. The first step isolates two videos, one of the forehead area and one of the cheek area, the second step feeds one video per branch of the Siamese Neural Network, and in the third step, the signal of each of the two branches is summed to produce the HR of the subject. The advantage of the double-branch structure with equal weights found in this technique, is that it allows the model to learn both the heterogeneous and homogeneous features of the two ROI. This technique uses a black-box model, which in the context of the Care2Report might be considered a large drawback. On the other hand, the results are the model are always cross-checked by the care provider at the end of the examination, which could render the use of a black-box model overall safe. It would therefore be interesting to consider using a deep learning model for the rPPG processing step in order to capture HR and other vital parameters.

5 PDD diagram

In this section, the PDD diagrams of the Care2Report project and rPPG technique are drawn and described, with their activity concept tables immediately following the respective PDD. Many of the concepts described in the concept tables do not have a source as the papers from which the technique is taken do not describe the deliverables at each step, but rather focus on the series of activities necessary in order to produce the final deliverable. The names of the intermediate deliverables were therefore chosen during the creation of this paper, and do not have an exact match in the original papers.

The first PDD shown in figure 1 concerns the Care2Report project. It is a streamlined and simplified version of what the Care2Report project PDD might look like, adapted in order to highlight the role that the rPPG technique would hold inside the system. It is worth noting that the rPPG software is part of the Care2Report software, but their activities have been represented separately in order to highlight the role of the rPPG software within the system. Closed complex activities are common, due both to the modular nature of the Care2Report project which complicates the description of activities such as "Set up Care2Report instruments" and due to complex transformations applied to the data in order to produce a summarized report of a consultation as is the case for the "Interpretation Stage" and the "Generate Report" activities.

The accompanying activity and concept tables in table 2 and 3 describe all the activities and concepts present in the Care2Report PDD diagram.

The second PDD shown in figure 2 represents the rPPG technique described by Kooij and Naber (2019). The decision to model the technique described in this specific paper rather than the one described in the paper by Verkruysse et al. (2008) is due to the inability to properly apply the latter to the Care2Report method due to multiple steps requiring manual interventions which would directly conflict with the principles of the Care2Report project. Furthermore, multiple steps described in this PDD could be swapped with alternative ones, as mentioned previously in the paper, or be deleted in favour of single activities capable of covering multiple steps at once, as is the case for deep learning. This PDD is therefore expected to be rapidly updated and change in the process of finding the technique or combination of techniques best-suited for the purposes of the Care2Report project. Keeping track of the method rationale of the rapidly evolving PDD could therefore be crucial in order to find an optimal solution.

Finally, the accompanying activity and concept tables in table 4 and 5 describe all the activities and concepts present in the rPPG PDD diagram. The activity table provides no actor as every activity is performed by the rPPG software. Furthermore, since as previously mentioned the concepts mentioned in the concept table were named as part of this paper, not all have sources per se, but the activity table sources every activity which produces those very concepts. It is then possible to trace each concept to an activity, and therefore a source, in the original paper by van der Kooij and Naber (2019).

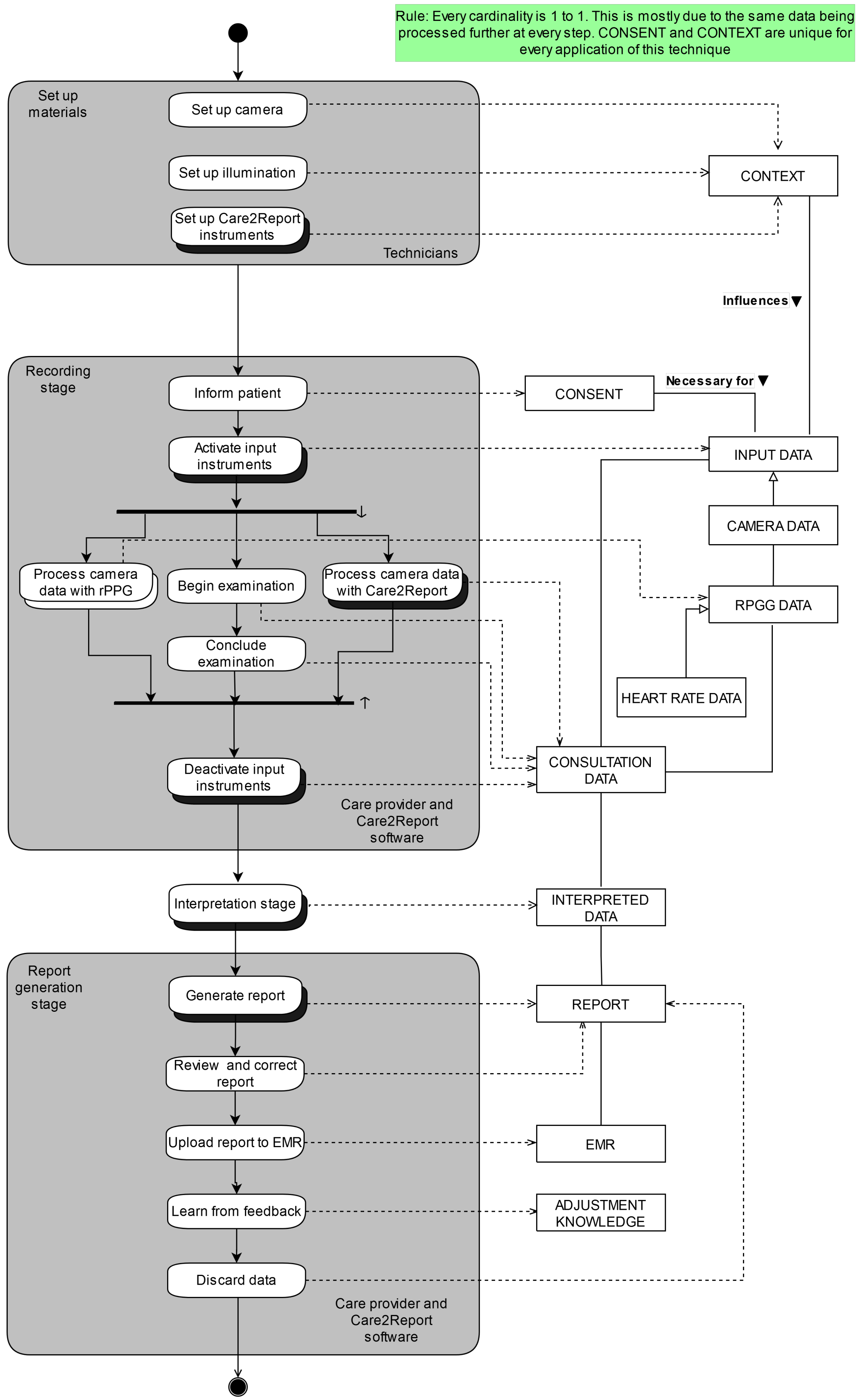

Figure 1: PDD of the Care2Report system

Activity	Sub-Activity	Description
Set up materials	Set up camera	Set up the camera in a stable position, pointed towards a body part of the subject. The position and type of camera are part of the CONTEXT. The camera is set up by a technician.
	Set up illumination	Illumination can be natural, artificial, or both. The type and intensity of the illumination are part of the CONTEXT. The illumination is set up by a technician.
	Set up Care2Report input instruments	Care2Report input instruments are generic and interchangeable by design (Maas et al., 2020). Their type and specific attributes are part of the CONTEXT. The instruments are set up by a technician.
Recording stage	Inform patient	The patient should be informed that they are going to be recorded by the care provider, they should be able to see the cameras, they should be able to see what is being recorded if so requested, and they should be informed that the recordings are discarded after the session ends (van der Kooij & Naber, 2019). Once CONSENT and its terms have been agreed upon, the input instruments can be activated.
	Activate input instruments	The instruments are turned on by the care provider, with audio feedback confirming their successful activation. The instruments produce INPUT DATA and its specialization, CAMERA DATA.
	Begin examination	The care provider begins the examination of the patient.
	Process camera data with rPPG	The rPPG software, part of the Care2Report software, processes the camera data and generates RPPG DATA and HEART RATE DATA (van der Kooij & Naber, 2019). See figure 2 for the PDD of this activity.
	Process camera data with Care2Report	The Care2Report software processes INPUT DATA, HEART RATE DATA, and RPPG DATA and generates CONSULTATION DATA (Maas et al., 2020).
	Conclude examination	The medical practitioner concludes the examination of the patient
	Deactivate input instruments	The input instruments are turned off by the care provider.
Interpretation stage		The Care2Report software processes CONSULTATION DATA into INTERPRETED DATA (Maas et al., 2020).
Report generation stage	Generate report	A natural language report is generated by the Care2Report software (Maas et al., 2020).
	Review and correct report	The care provider reviews and corrects the report. (Maas et al., 2020)
	Upload report to EMR	The reviewed and corrected report is uploaded to the EMR by the Care2Report software.
	Learn from feedback	The Care2Report software learns from the review of the report. (Maas et al., 2020)
	Discard data	All recorded data is discarded at the end of the process for privacy reasons by the Care2Report software.

Table 2: Activity table of the PDD of the Care2Report system

Concept	Description
CONTEXT	CONTEXT contains attributes that could influence the INPUT DATA such as the types of instruments used and the current illumination. While this concept does not have a specific source, papers on this technique clearly define the context or environment in which it was applied (van der Kooij & Naber, 2019) (Verkruysse et al., 2008).
CONSENT	CONSENT is necessary in order to start gathering input data. (Maas et al., 2020)
INPUT DATA	Input instruments gather INPUT DATA (Maas et al., 2020).
CAMERA DATA	CAMERA DATA is a specialization of INPUT DATA, gathered by the camera instrument (van der Kooij & Naber, 2019) (Verkruysse et al., 2008).
RPPG DATA	RPPG data is all RPPG data not related to heart rate, and it is derived from CAMERA DATA through the rPPG processing (Verkruysse et al., 2008). See table 2 for the PDD of this activity.
HEART RATE DATA	HEART RATE DATA is a specialization of RPGG DATA obtained through the rPPG processing (van der Kooij & Naber, 2019) (Verkruysse et al., 2008). See table 2 for the PDD of that activity.
CONSULTATION DATA	CONSULTATION DATA is generated by the Care2Report software (Maas et al., 2020). The specifics of the implementation are irrelevant to the rPPG technique due to the modularity of the Care2Report software.
INTERPRETED DATA	INTERPRETED DATA is generated by the Care2Report software (Maas et al., 2020).The specifics of the implementation are irrelevant to the rPPG technique due to the modularity of the Care2Report software.
REPORT	The REPORT is a summary of the consultation (Maas et al., 2020). It contains all the relevant data regarding the examination, and can be edited by the medical practitioner before being uploaded to the EMR.
EMR	An EMR is a digital record of the medical history of a patient.
ADJUSTMENT KNOWLEDGE	ADJUSTMENT KNOWLEDGE is the knowledge gathered by the Care2Report software in order to adapt to each care provider (Maas et al., 2020).

Table 3: Concept table of the PDD of the Care2Report system

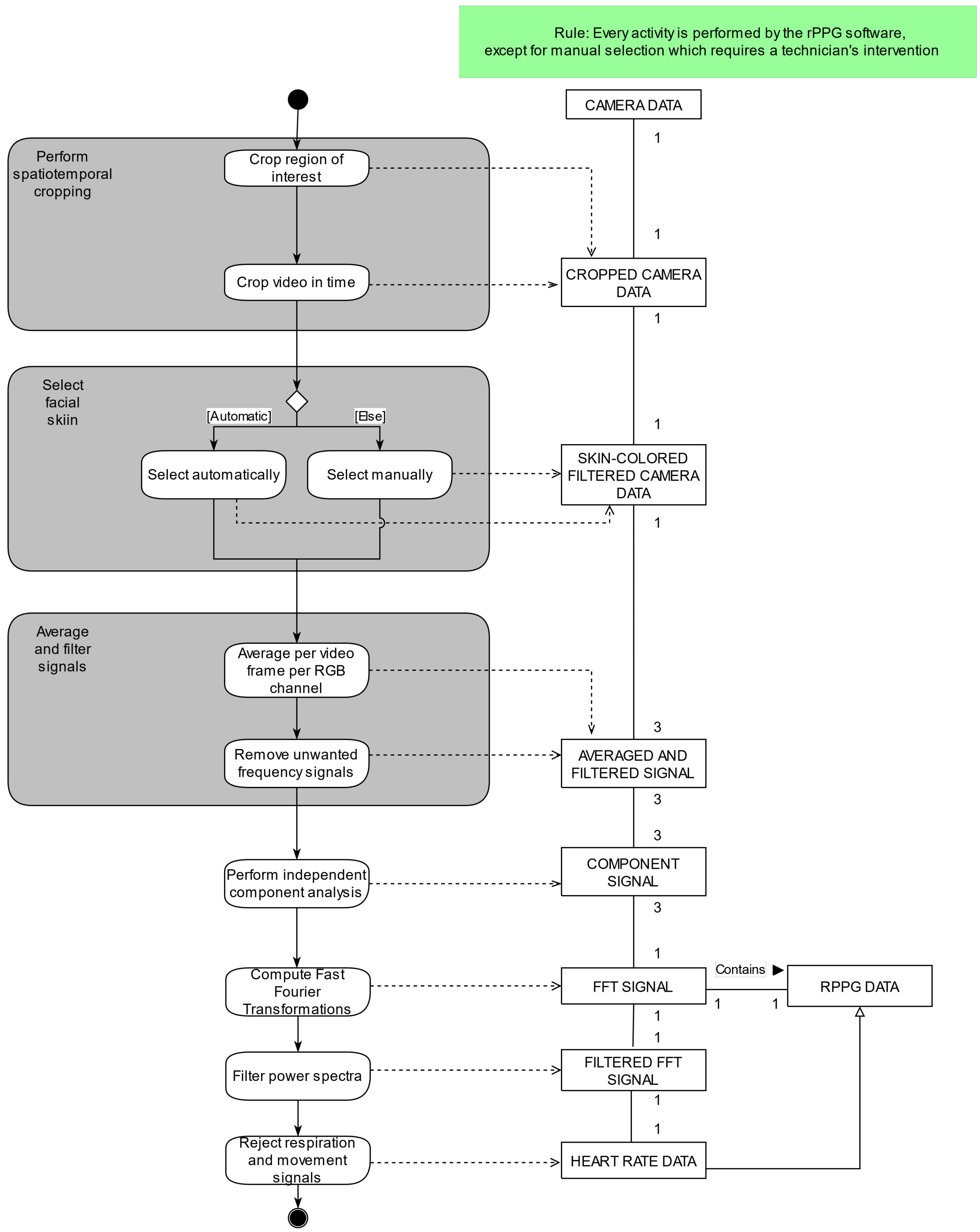

Figure 2: PDD of the rPPG technique

Activity	Sub-Activity	Description
Perform spatiotemporal cropping	Crop region of interest	The CAMERA DATA is cropped around a region of interest in order to remove irrelevant background objects (van der Kooij & Naber, 2019).
	Crop video in time	Parts of the CAMERA DATA that are deemed noisy or not useful should be removed (van der Kooij & Naber, 2019).
Select facial skin	Select automatically	Automatic detection of skin within a picture can be achieved with the k-means clustering approach (van der Kooij & Naber, 2019). This process removes irrelevant features from the image providing SKIN-COLOR FILTERED CAMERA DATA (van der Kooij & Naber, 2019).
	Select manually	Manual selection of skin within a picture is achieved by selecting pixels in the first frame of the video that captured the hues of the skin and using them to filter the frames of the video. This process removes irrelevant features from the image providing SKIN-COLOR FILTERED CAMERA DATA(van der Kooij & Naber, 2019).
Average and filter signals	Average per video frame per RGB channel	The average pixel per frame per RGB channel is computed from SKIN-COLORED FILTERED CAMERA DATA (van der Kooij & Naber, 2019) and set as a function of time.
	Remove unwanted frequency signals	Unwanted frequencies are removed from the function generated by the previous step through a filter. The type of filter used depends on the type of rPPG data being gathered(van der Kooij & Naber, 2019).
Perform independent component analysis		The AVERAGED AND FILTERED SIGNAL is used as input for Independent Component Analysis to extract the COMPONENT SIGNAL(s) (van der Kooij & Naber, 2019).
Compute Fast Fourier Transformation		The COMPONENT SIGNALS are Fast Fourier Transformed to extract FFT SIGNAL(s) (van der Kooij & Naber, 2019).
Filter power spectra		The FFT SIGNAL(s) are filtered to select the power peak corresponding to the heart rate. FILTERED FFT SIGNAL(s) are the result of this process (van der Kooij & Naber, 2019).
Reject respiration and movement signals		In order to remove the peak of the respiration rate, van der Kooij and Naber (2019) removed a peak according to the IF-THEN-ELSE rules that they named "respiration rejection". This rule produces the peak that corresponds in frequency to the heart rate. The result of this activity is the HEART RATE DATA(van der Kooij & Naber, 2019).

Table 4: Activity table of the PDD of the rPPG technique

Concept	Description
CAMERA DATA	CAMERA DATA is a specialization of INPUT DATA, gathered by the camera instrument (van der Kooij & Naber, 2019) (Verkruysse et al., 2008).
CROPPED CAMERA DATA	CROPPED CAMERA DATA is CAMERA DATA which has been cropped.
SKIN-COLOR FILTERED CAMERA DATA	SKIN-COLOR FILTERED CAMERA DATA is CROPPED CAMERA DATA after being filtered by skin-color.
AVERAGED AND FILTERED SIGNAL	AVERAGED AND FILTERED SIGNAL is the signal produced by a SKIN-COLOR FILTERED CAMERA DATA after being averaged per frame per RGB channel, set as a function of time, and then filtered to remove unwanted frequencies.
COMPONENT SIGNAL	COMPONENT SIGNAL is one of the main components of an AVERAGED AND FILTERED SIGNAL
FFT SIGNAL	FFT SIGNAL is the Fast Fourier Transformation of a COMPONENT SIGNAL.
RPPG DATA	RPPG data is all RPPG data not related to heart rate, and it is derived from CAMERA DATA through the rPPG processing.
FILTERED FFT SIGNAL	FILTERED FFT SIGNAL is an FFT SIGNAL after being filtered to remove power peaks that do not correspond to the heart rate.
HEART RATE DATA	HEART RATE DATA is the heart rate of the subject throughout the examination. It is derived by the power peaks of the FILTERED FFT SIGNAL after applying the "respiration rejection" rule (van der Kooij & Naber, 2019).

Table 5: Concept table of the PDD of the rPPG technique

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