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4D Computed Tomography

MASTER'S THESIS

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Supervisor

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Institute of Electronic Sensor Systems

Graz, April 2018

AFFIDAVIT

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Signature

Acknowledgments

This Master's Thesis was done at the Institute of Electronic Sensors Systems, TU Graz. This instute equipped me with all the materials and a workplace I needed for my work. Thanks to my supervisor Univ.-Prof. Mag.rer.nat. Dr.rer.nat. Alexander Bergmann for leading me through this thesis with his knowledge, good ideas and support even at unexpected testing results.

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Graz, April 2018 David Niederkofler

Kurzfassung

Um Lungenkrebs mittels Strahlentherapie behandeln zu können, ist eine vorausgehende Bestrahlungsplanung notwendig. In vielen Fällen basiert diese auf einer zeitaufgelösten Computertomographie (4DCT), unterstützt von einem Atemerkennungssystem, welches ein Atemsignal an den Computertomographen sendet. Während der Erfassung muss der Patient ruhig und regelmäßig atmen, da es sonst zu fehlerhaften Daten bis hin zum Datenverlust kommen kann. Kommt es zu einem Datenverlust, so muss die 4DCT-Unterstuchung wiederholt werden, was neben erhöhtem Zeit- und Kostenaufwand auch eine höhere Strahlenbelastung für den Patienten zur Folge hat. Im schlimmsten Fall kann es dazu kommen, dass die Planung abgebrochen werden muss und es zu keiner Strahlenbehandlung kommt.

Da das Atemerkennungssystem bei unregelmäßiger Atmung kein verwertbares Atemsignal an den Computertomographen senden kann, wurde in Zusammenarbeit mit der Universitätsklinik für Strahlentherapie-Radioonkologie in Graz eine bereits entwickelte Methode zum datenverlustfreien Erfassen von Patientendaten weiterentwickelt, an einem Thorax-Phantom getestet und bis zur Anwendung an Patienten gebracht. Ein extern erzeugtes, regelmäßiges Atemsignal, welches später im CT-System nachträglich angepasst wird, kann einen Datenverlust während der Untersuchung verhindern. Das nachträgliche Anpassen des Atemsignals sorgt für eine genauere Rekonstruktion der CT-Daten, anhand welcher die Bewegung und Ausdehnung des Tumors im genauer bestimmt werden kann, falls es zu einer unregelmäßigen Atmung kam. Diese Methode sollte am in der Universitätsklinik für Strahlentherapie und Radioonkologie stehenden Computertomographen Toshiba Aquilion LB V.3 mittels Thorax-Phantom optimiert werden. Nach ausgiebigem Testen wurde jedoch festgestellt, dass an diesem Computertomographen das nachträgliche Anpassen des Atemsignals keinen Einfluss auf die Rekonstruktion der CT-Daten hat. Der einzig ausschlaggebende Faktor ist das während der Untersuchung gesendete Atemsignal.

Um einen Vergleich mit einem anderen CT-Gerät zu haben, wurden einige Messungen an einem CT Brilliance Big Bore der Fa. Philips der Außenstelle der LKH Graz in Leoben gemacht. Dort konnte man sehen, dass das nachträgliche Verändern des Atemsignals einen Einfluss auf die Rekonstruktion hat. Eine sich verändernde Rekonstruktion bedeutet, dass die entwickelte Methode prinzipiell, zum Beispiel am CT in Leoben, angewandt werden könnte, was eine bessere Rekonstruktion der Patientendaten zur Folge hätte. Da der CT an der Universitätsklinik in Graz nicht auf ein sich nachträglich änderndes Atemsignal reagiert, kann die Methode an diesem speziellen Modell nicht angewandt werden. Dennoch wird diese vorgestellt, welche an einem richtig funktionierenden CT umgesetzt und noch weiter verbessert werden könnte.

Abstract

To cure lung cancer with a radiotherapy, a prior radiation planning is needed. Most of the time, this planning is based on a time-resolved computed tomography (short 4DCT), supported by a breath rate recognition system that sends a breathing signal to the computed tomographic device. The patient needs to breath in a periodical and uniform way, otherwise the 4DCT-scan has faulty results or even data losses. If a data loss occurs, the scan needs to be repeated. A repeated scan means a higher radiation exposure for the patient, but also the costs and expenditure of time are rising. In the worst case, the planning is aborted and there will not be any further RT for the patient.

If there are any irregularities in breathing while the computed tomographic device is scanning, the breath rate recognition system cannot send a usable signal. Due to that fact, an already developed method for improved 4D computed tomography data acquisition for preventing data losses was developed further. In cooperation with the Medical University of Graz, Department of Therapeutic Radiology and Oncology this method was tested on a thorax phantom and in the end applied in a practical way. An external device sends a periodical breathing signal that prevents data losses. This signal is edited in a second step after the CT-scan. The subsequent editing of the breathing signal ensures a better reconstruction of the patient data which allows the doctors do determine the location and size of the tumour more precisely.

This method should have been tested on the computed tomography device Toshiba Aquilion LB V.3 at LKH-Univ.Klinikum Graz, Department of Therapeutic Radiology and Oncology. After several tests it was discovered that the subsequent editing of the breathing signal does not have any impact on the reconstruction. The only crucial factor is the breathing signal that is sent during scanning.

In order to compare the behaviour of the Toshiba computed tomography device, some tests were done with a Philips Brilliance Big Bore CT at the branch offices in Leoben. The second computed tomographic device showed some reactions to the subsequently edited breathing signal. This means that the newly develped method for better reconstruction can be applied, i.e. at the CT in Leoben. Due to the fact that the computed tomographic device at the LKH-Univ.Klinikum Graz does not react to the subsequently modified breathing signal, the method cannot be applied to this specific device. Nevertheless the method, that could be applied on a correctly working CT, is presented.

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Chapter 1

Theoretical Background

1.1 Radiotherapy

Radiotherapy (RT) is the use of ionising radiation to heal diseases or to delay their progress. Most commonly the used radiation are gamma-, roentgen- and electron beams. Radiotherapy is used for benign and malignant tumours. In contrast to chemotherapy radiotherapy is only a local treatment and the tumour-killing radiation is only applied to a specific region. RT can solely be used as a cancer treatment, combined with chemotherapy or as a treatment before or after an operation. Especially for lung cancer the RT is a good alternative to an conventional operation, because latter is combined with a lot of risk and pain for the patients.

1.1.1 Effect of the Radiotherapy

The ionised radiation destroys tumorous tissue. It damages the hereditary material of the malicious cells so that their cell division stops. This makes the tumours shrink or even disappear.

Unfortunately the ionising radiation is not specific which means that also healthy cells are affected. However the repair systems of the cells try to fix the damaged hereditary material. This effect is stronger with healthy cells and less applied with tumorous cells. This means that the healthy cells regenerate and the tumorous ones are dying. To allow the intact cells to regenerate, the RT must be planned that the total applied dose of radiation is split into several meetings (fractions).

The doctor chooses the radiation dose that is applied to the tumorous tissue. The healing dose is between 40 and 70 Gray (Gy). As previously said, this dose is not applied at once, instead it is applied in several fractions of about 2 Gy. This increases the tolerability and the risk of lasting damages is reduced. Newer methods of more precise radiation allow to apply more radiation at once because fewer intact tissue is hit. With this advantage the regeneration of the healthy cells does not have

a big impact any more.

The most extreme form of radiation is the radiosurgery. A very high dosage is applied in one day. This reduces the time of the therapy and a big part of the tumorous cells are destroyed at one. But the drawback is that the patient is fraught with a lot of cell debris.

1.1.2 Categories of Radiotherapy

Generally said, radiotherapy can be separated into two different approaches: radiotherapy from the outside with a linear accelerator and radiotherapy from the inside with sealed radionuclides.

- In radiotherapy from the outside the treatment is done trough the skin. The used devices are linear accelerators. The patient lies on a so called couch and he is fixed there as no movement is allowed during the radiation. The patient couch itself and the linear accelerator are movable. This allows to change the direction of the radiation and the location of irradiated area. Even the respiration can be calculated into the radiation process to balance the movement of the patient's thorax [7].

  Radiotherapy from the outside can be combined with chemotherapy to a so called radiochemotherapy. The chemotherapy increases the vulnerability of the tumorous tissue which increases the efficiency of the RT. Not every chemotherapeutical drug is compatible to the radiotherapy. Therefore a very good coordination of both therapies is needed [7].

- Radiotherapy from the inside is called brachytherapy. Here the radiation source is located directly at the tumour's location. The radiation has a range of only a few millimetres and its dose is controlled by the exposure duration, the activity and half-life period of the radionuclide. The brachytherapy has the advantage that the surrounding intact tissue is not harmed as much as in the radiotherapy from the outside. The brachytherapy can be applied at cervical cancer, prostate cancer head or neck tumours [7][2, p.541-650].

1.1.3 Preparation of a Radiotherapy

The goal of a radiotherapy is to get as much dose as possible into the tumorous tissue but the healthy tissue should get as little as possible. Therefore a RT needs to be planned very carefully. In the run-up to it, every part of the body, that is going to be irradiated, needs to be scanned with a so called computed tomography (CT). In order to get information about the inside of the body, the radiopaquiness is measured. After that, a three-dimensional image is computed and the best order

of the irradiation fields is computed. Summarising it can be said that the computed tomography based planning of the radiotherapy enables to predict how much radiation dose arrives at the tumorous tissue [7].

1.2 Computed Tomography

In order to have as much information of the patients body as possible, a computed tomographic scan (CT-scan) is necessary.

A general X-ray scan delivers a two-dimensional image of a certain part of the body. As opposed to that, a CT-scan delivers cross sections of the scanned body. These cross sections can be uses to constitute three-dimensional structures from the inside of a body. This does not only allow to detect diseases inside the body but also to determine their location and size.

1.2.1 Function of the Computer Tomography

Exactly as in the normal X-ray scan the principle of different roentgen radiation absorbtion depending on the different tissue is used. The more dense the tissue is, the more radiation is absorbed. This is displayed in different gray tones: Bones are absorbing almost all of the roentgen radiation. Therefore they are white on the resulting scan. The lung, which is full of air does not absorb much of the radiation which results in dark sections [9].

In a X-ray scan, the absorbtion of all tissues in direction of the radiation beam are summed up. Therefore it is only possible to detect tissues that vary much in absorbtion [9].

The CT does not have this disadvantage. Instead of a 2D-image a cross section is generated. A modern CT-device consists of a x-ray tube that generates a fan beam and a detector field with several sensors. The sensors detect the amount of passed roentgen radiation that was not absorbed by the body. The big difference compared to the usual x-ray scan is that the x-ray tube and detector are rotating around the scanning object. This means that there are several x-ray scans from different directions of the same region of the body [9].

From the different projections from different directions of the same region of the body, the CT computes a cross-sectional image. Having such a cross-sectional image it is easier to detect and locate possible diseases. Usually, more than one CT-scan is performed. There are various scans of the body to have multiple images respectively cross-sections [9].

Nowadays the common CT-devices rotate the tube and detector around the patient while he is pushed through the bore of the CT-device with a constant velocity.

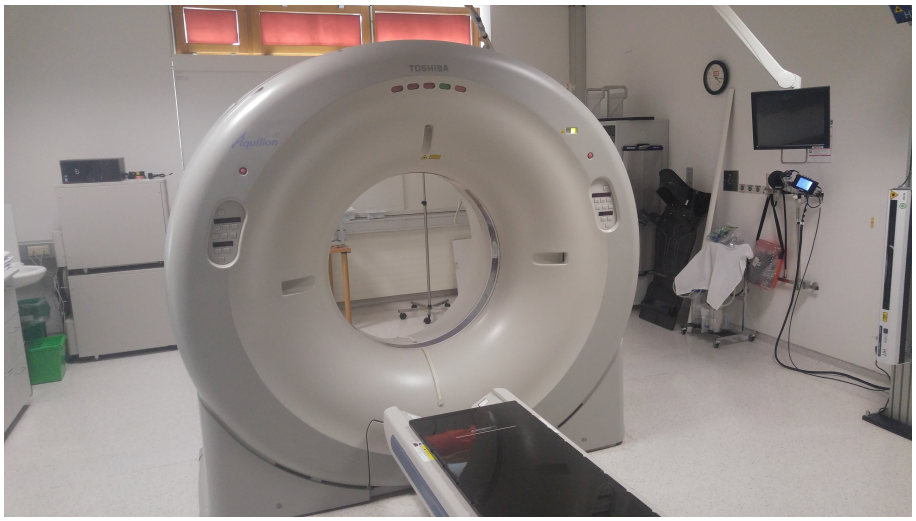


Figure 1.1: Computed Tomography Device Toshiba Aquilion LB V.3

This results in a helical scanning shape of the radiation beam. This procedure allows to scan a bigger part of the body in one pass. Afterwards it is possible to extract specific cross-sections but also to generate a 3D model of the whole scanned area [9].

During scanning it is crucial that the patient is not moving. Already very little movements during scanning can result in blurry images. In the worst case the tumorous tissue cannot be separated and located clearly. This means that the CT-scan needs to be repeated, which results in a higher radiation exposure to the patient.

The computed tomography can be applied for body parts that usually do not move while breathing. In case of lung cancer it is not possible to determine the exact location and size of the tumorous tissue with a CT-scan. In most cases the tumour moves while breathing. This means that it also moves while scanning and may appear smaller than it actually is on the CT-scans. This results in a wrong irradiation planning that may cause the irradiation of the wrong section of the body. This is where the so called 4D Computer Tomography (4DCT) comes in. The 4DCT is able to do time-resolved scans of the body. This is primarily applied to lung cancer radiotherapy.

1.3 Four Dimensional Computed Tomography

The continuous improvement of the computed tomographic approach lead to the possibility of making CT-scans of periodically moving objects. This is exactly the case when scanning the thorax of a patient. The lung expands during breathing and therefore also the tumour moves [10].

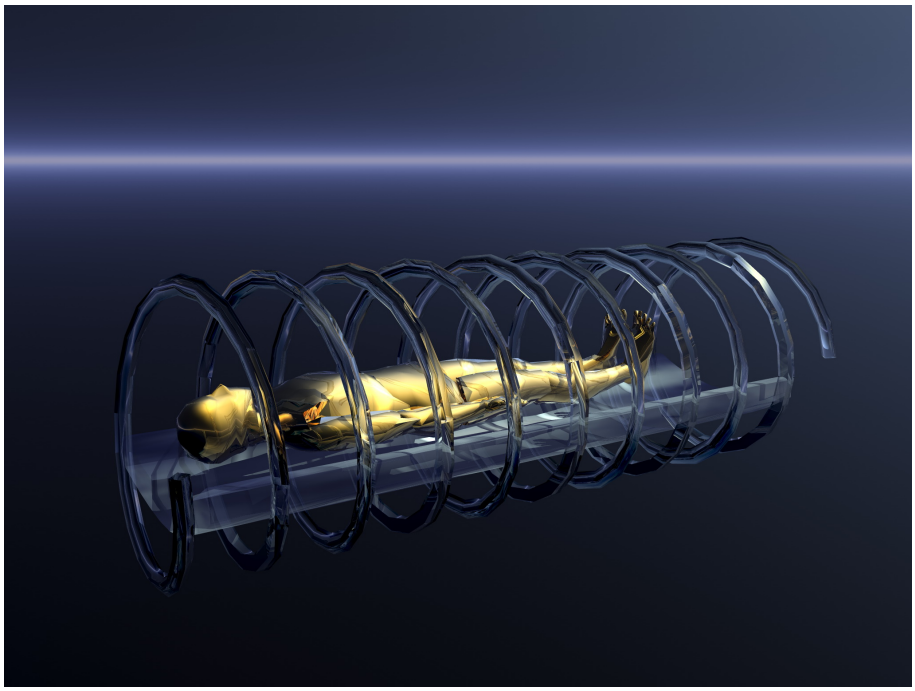


Figure 1.2: Schematic representation of a helical CT

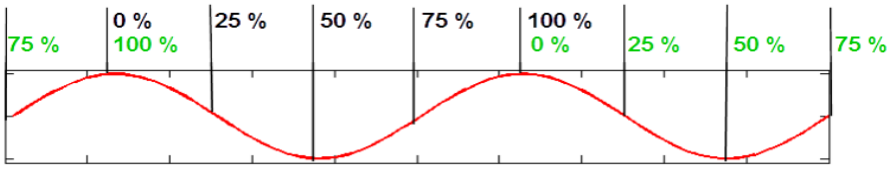


Figure 1.3: Breathing phases [10]

At every couch position, there are multiple scans for the period of a complete breathing cycle. This means that there is a scan for every section of the scanned object for every phase during respiration e.g. when completely inhaled or exhaled.

The division of the individual breathing phases is done on the basis on a curve of sinusoidal shape.

In order to view at the cross sections in a time-resolved manner, it is necessary to assign them to a certain breathing phase. This is why there is a separate device that analyses the movement of the thorax during the CT-scan. Whenever it reaches the same position again, most commonly the point of maximum inhalation, the analysing device sends a signal to the CT, referred as triggers in this Master's thesis. In the rest of this Master's thesis, the separate signals are called triggers. All the triggers in total are called breathing signal.

Depending on the breath rate, the CT must adapt the rotation speed of the roentgen tube and the velocity of the patient couch in order to be able to scan every section of the body for a whole breathing cycle. To adapt the different speeds, it is

necessary to know the breath rate already before the CT-scan starts. The name of this whole approach is 4D Computed Tomography or 4DCT.

The procedure of doing a 4DCT takes longer than an usual CT, but the advantage of the time-resolved CT is the significantly higher information yield.

In figures 1.4 and 1.5 two data sets including axial, sagittal and coronal cuts of a patient thorax in 0% phase and 50% phase can be seen. It can be observed that the tumorous tissue is moving while breathing. Therefore the irradiation area marked in red is large enough to cover all the possible positions of the tumorous tissue in order to make sure that it is always hit by the linear accelerator's beam. This area is called the Planned Target Volume (PTV) [10].

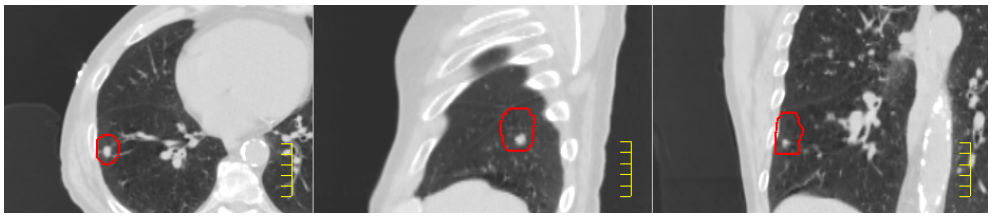


Figure 1.4: Thorax at 0% Phase [10]

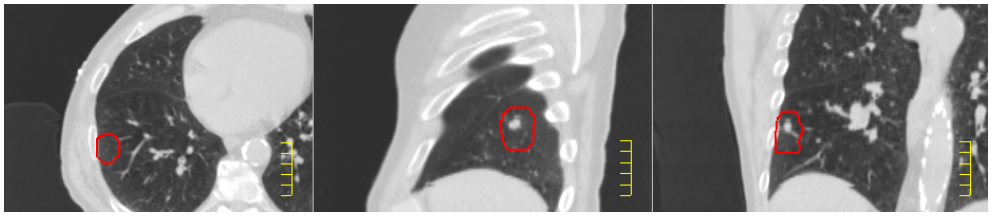


Figure 1.5: Thorax at 50% Phase [10]

1.4 Varian Real-Time Position Management Respiratory Gating

The Varian Real-Time Position Management Respiratory Gating system (RPM-system) is the device that analyses the patient's thorax movement and sends the breathing signal to the CT device [6].

It consists of an infrared camera, a so called marker block and a PC that runs the software of the whole system. The camera is mounted at the end of the patient's couch and records the movement of the marker block. This marker block has six markings on it that allow the camera to detect its spatial movement. The marker block is placed on the abdomen of the patient so it is possible to record his respiration behaviour and to detect the peaks of full inhalation or exhalation [6].

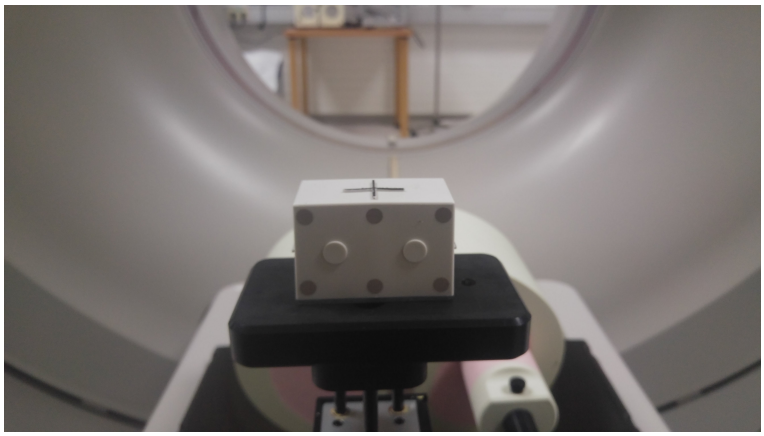


Figure 1.6: RPM-system's marker block

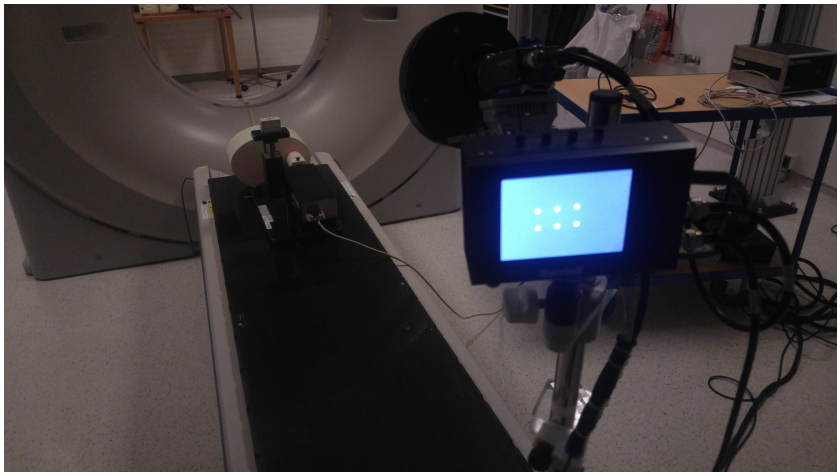


Figure 1.7: RPM-system's camera

In order to send the triggers of the breathing signal, the RPM-system needs to first to learn and observe the amplitude and breath rate of the patient. This is done before the CT-scan starts. If the RPM-system can detect a regularity in breathing, it can determine the various breathing phases and send a trigger e.g. at the 0% phase. This is the first mode of operation. The second mode is just sending a trigger if the breathing amplitude exceeds a certain amplitude [6].

The RPM-system works very well for uniform breathing. Its big disadvantage is that it cannot react quickly to breathing dropouts or variance in the breath rate. The learning process is too slow which results in a failure of sending the breathing signal.

This failure of sending the breathing signal can cause the loss of CT-data while scanning: Just before the CT-scan the Computed Tomographic device records the breath rate and based on this, it calculates the optimal shape of the scanning helix.

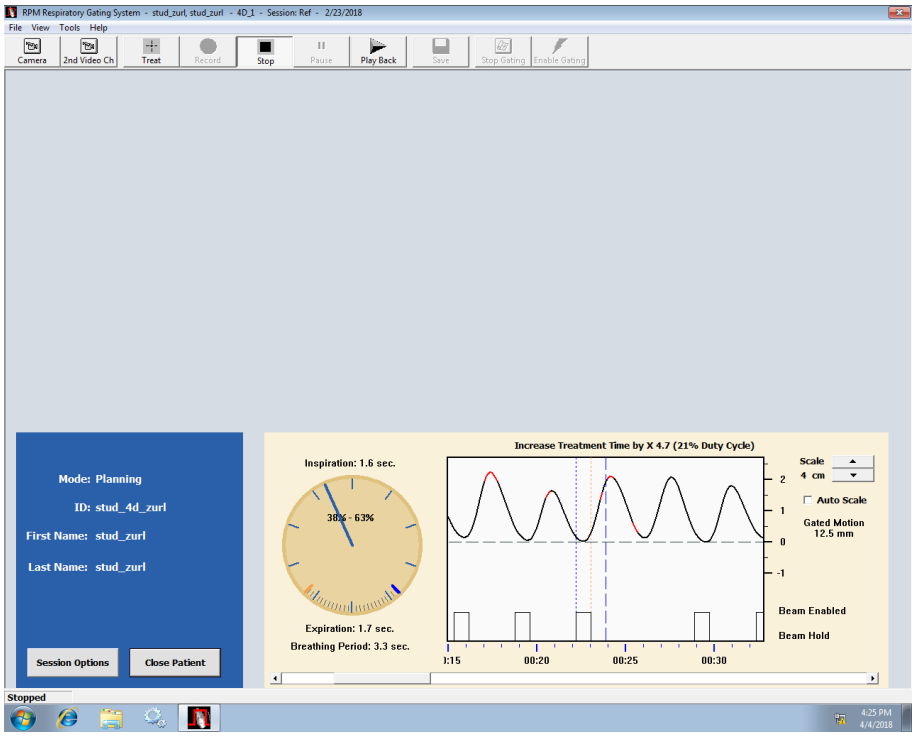


Figure 1.8: Interface of the RPM Gating System [6]

During the actual scanning, the CT device just records the breathing signal for later reconstruction. If it scans a whole section without getting any breathing signal, the section is considered lost and cannot be used for reconstruction. If the section of data loss is exactly at the tumour's location, the whole procedure of the 4DCT scan needs to be repeated in order to have a good basis of planning the radiotherapy. A second 4DCT scan means a higher radiation exposure for the patient, that should be avoided. Therefore it is absolutely necessary to continuously send the breathing signal to avoid data losses.

1.5 CIRS Thorax Phantom

As it is not possible to get usable results of one-time scans of patients, a dynamical Computerized Imaging Reference Systems (CIRS) Thorax Phantom is used to create some reproducible tests of the breathing dropouts. This phantom has a cylindrical shape and is made out of materials that are similar to human tissue to make simulations of a real thorax. Outside the middle of the phantom there is a hole, where a cylinder lies in. This cylinder has a cut out with a small sphere in it that simulates the tumour. The cylinder is attached to a robot that moves the cylinder inside the thorax phantom. With this it is possible to simulate a moving tumour inside the thorax.

Next to the thorax there is a so called surrogate. This is a platform that simulates the lifting and sinking of the abdomen. The marker block of the RPM-system is placed on this platform and the infra-red camera can record the simulated respiration curve.

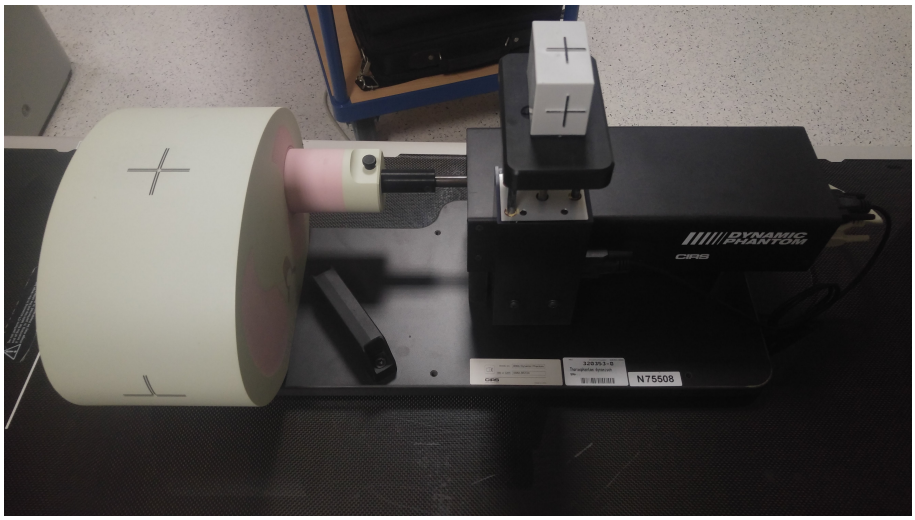


Figure 1.9: CIRS Dynamic Thorax Phantom

1.6 Limitations of Medical Systems and Studies, Ethics Committee

The goal of this Master's thesis is to develop a new method to prevent the data losses of a 4DCT scan. The problem is that all the used devices are medical devices. This means that they must not be manipulated in any way. This makes the development harder as everything new must be done from the outside [3].

In order to be allowed to do some tests on the medical devices, the Ethics Committee at Med Uni Graz needs to grant permission to do so. They observe clinical trials of new products, new medical methods and research on humans. All these tests and new methods must be in accordance with the Declaration of Helsinki [5] and the ICH-GCP Gudelines [4]. They are also checking whether all the legal provisions of the Austrial Medicinal Products Act, the Austrian Medical Devices Act, the Styrian Hospitals Act, Federal Hospitals and Health Spas Act are fulfilled [3].

For every new study a request form is sent to the Ethics Committee that checks for the feasibility and ensures the ethical conduct of the research. This request form contains multiple pages with the title of the study, its probable duration, a description and many other details. Figure 1.10 and 1.11 show short extracts how

the request form for the study of this Master's Thesis looks like.

As the development and testing of this presented method needed research on humans, the Ethics Committee at Med Uni Graz granted permission to do so for this Master's Thesis. The presented method is only applicable at the LKH Graz and the developed devices must not be used for any other application than stated in this thesis.

Antrag

Version 6.4 vom 12.06.2012 **Bitte immer die *aktuelle* Version verwenden (*http://ethikkommissionen.at*)!**

Dieses Formular soll für Einreichungen bei österreichischen Ethikkommissionen verwendet werden.
Es setzt sich aus einem allgemeinen Teil A - Angaben zur Studie und zum Sponsor -
und aus einem speziellen Teil B - Angaben zu der/den einzelnen Prüfstelle(n) - zusammen.
Bei Einreichungen für mehrere Zentren (Prüfer/innen) muss nur der Teil B an das jeweilige Zentrum angepasst werden.

Adresse der Ethikkommission (optional)	Raum für Eingangsstempel, EK-Nummer, etc. Bitte Freilassen!

ANTRAG AUF BEURTEILUNG EINES KLINISCHEN FORSCHUNGSPROJEKTES

für folgende Prüfer/innen bei folgenden österreichischen Ethikkommissionen:

► *Bitte **alle** Ethikkommissionen eintragen, an die der Antrag gesendet wird **(Kurzbezeichnung!)*** ◄
► *Im Falle einer **multizentrischen Arzneimittelstudie** ist die **Leitethikkommission** als erste anzuführen!* ◄

Zuständige Ethikkommission	Prüferin/Prüfer (lokale Studienleitung)
Medizinische Universität Graz	**Univ. Prof. Dr. K. Kapp**

Teil A

1. Allgemeines:

1.1 Projekttitel: **Methode zur verbesserten Datenerfassung bei einer 4D-Computertomographie als Planungsgrundlage für Hochpräzisionsbestrahlungen**

1.2 Protokollnummer/-bezeichnung: 1.2.1 EudraCT-Nr.:

1.3 Datum des Protokolls: 1.3.1 ISRCTN-Nr.:

1.4 Daten der beiliegenden Amendments: 1.4.1 Nr. 1.4.2 Datum:
1.4.3 Nr. 1.4.4 Datum:
1.4.5 Nr. 1.4.6 Datum:

1.5 Sponsor / RechnungsempfängerIn (Kontaktperson in der Buchhaltung):

	Sponsor	RechnungsempfängerIn
1.5.1 Name:	**Univ. Klinik f. Strahlentherapie-Radioonkologie**	
1.5.2 Adresse:	**Auenbruggerplatz 32**	**8036 Graz**
1.5.3 Kontaktperson:	**Univ. Prof. Dr. Karin Kapp**	
1.5.4 Telefon:	**+43 316 385 83325**	
1.5.5 FAX:		
1.5.6 e-mail:	**karin.kapp@medunigraz.at**	
1.5.7 UID-Nummer		(wenn nicht gleich wie „Sponsor“)

Figure 1.10: Request form for the new study [3]

7. Strukturierte Kurzfassung des Projektes (*in deutscher Sprache, kein Verweis auf das Protokoll*)

7.1 Wenn Original-Projekttitel nicht in Deutsch: Deutsche Übersetzung des Titels:

Methode zur verbesserten Datengenerierung bei einer 4D-Computertomographie als Planungsgrundlage für Hochpräzisionsbestrahlungen

7.2 Zusammenfassung des Projektes (Rechtfertigung, Relevanz, Design, Maßnahmen und Vorgehensweise):

Eine radioonkologische Behandlung erfordert die genaue Kenntnis von Lage, Größe und Ausbreitung des Tumors. Dazu werden Schnittbilder mit einem Computertomographen (CT) erstellt, die dann eine Berechnung und Optimierung der Strahlung im menschlichen Körper ermöglichen. Da die CT ein sehr schnelles Verfahren ist, erscheinen bewegte Objekte eingefroren oder verschmiert. Eine Hochpräzisionsbestrahlung mit ablativen Dosen (Stereotaxie) von Lungentumoren/-metastasen, sowie sämtliche im Oberbauch liegende Läsionen, benötigt jedoch die Kenntnis der atembedingten Tumorbewegung, um einerseits den gesamten Tumor bei der Strahlenbehandlung erfassen zu können und andererseits umgebendes gesundes Gewebe maximal zu schützen.

Um die Bewegung des Tumors während der Atmung darstellen zu können bedient man sich der vierdimensionalen Computertomographie (4D-CT). Die 4D-CT ist ein CT Aufnahmesystem, indem die Zeit als 4. Dimension dargestellt wird und die CT-Datensätze entsprechend der Atemphasen (Einatmung, Ausatmung...) rekonstruiert werden.

Mittels eines externen Messsystems (RPM Respiratory Gating System), das die Atmung aufzeichnet und bewertet, wird ein Signal am Beginn jedes Atemzyklus an die CT gesandt. Patientenbedingt (unregelmäßige Atmung, Husten) kommt es häufig zu Abweichungen, die eine exakte Rekonstruktion in allen Atemphasen nicht ermöglicht. Die Folge sind Streifenartefakte, die die Dosisverteilung im Bestrahlungsplan verfälschen. Auch die Volumina der Risikoorgane und ihre exakte Dosiseinschätzung werden dadurch verzerrt. Schlimmstenfalls führt dies zu Datenverlusten, so dass sämtliche Informationen über einen bestimmten Bereich verloren gehen und in den CT-Bildern nicht dargestellt werden können.

Mangelhafte Bilddatensätze führen zu Ungenauigkeiten in der Dosisberechnung im Tumor und umliegenden gesunden Gewebe. Eine Fehleinschätzung von Risikoorgandosen kann zu Nebenwirkungen, Spätfolgen und zusätzlichen Behandlungskosten führen.

Im Rahmen einer Masterarbeit in Kooperation mit der TU-Graz wurde eine Methode entwickelt, die ohne in die Durchführung der 4D-CT mit RPM-System einzugreifen durch Hinzunahme eines externen Triggers eine verbesserte Datensortierung ohne Datenverlust gestattet.

Durch den regelmäßigen externen Trigger werden alle (einschließlich aller Unregelmäßigkeiten) CT Daten aufgezeichnet und stehen bei allfälligen Veratmungen für Rekonstruktionen zur Verfügung, sodass eine neuerliche CT-Untersuchung, wie bis dato notwendig, vermieden werden kann.

7.3 Ergebnisse der prä-klinischen Tests oder Begründung für den Verzicht auf prä-klinischen Tests:

Die Funktionalität der Methode wurde durch Experimente an einem dynamischen Thorax-Phantom untersucht, welches sowohl periodische Bewegung als auch menschliche Atmung während einer 4D-CT Untersuchung simulieren kann. Die gewonnenen Daten wurden auf gleiche Weise verarbeitet wie dies bei realen Patienten der Fall wäre, um zu überprüfen, ob anhand der gesammelten Daten eine Bestrahlungsplanung möglich wäre.

Zunächst wurden Tests mit einer idealisierten, streng periodischen Bewegung durchgeführt, um die generelle Funktionalität zu überprüfen und um Referenzwerte für weitere Messungen zu generieren. Unter diesen Bedingungen wurden ausschließlich fehlerfreie Datensätze erzeugt. Im nächsten Schritt wurde eine definierte Störung in die Bewegung eingebracht, deren Ausmaß und Dauer genau bekannt waren, wodurch eine Idealisierung eines realen Störfalls getestet werden konnte. Hier traten bei Untersuchungen nach der konventionellen Methode die bekannten Fehler auf. Bei Wiederholung der Untersuchungen nach der neu entwickelten Methode konnten sämtliche Datenverluste vermieden, sowie für eine Bestrahlungsplanung brauchbare Daten generiert werden. Im letzten Schritt wurde die, während einer realen, misslungenen 4D-CT Untersuchung, aufgezeichnete Atembewegung eines Patienten in das Phantom eingespielt, um diese nachstellen zu können. Nach der konventionellen Methode wurde der Datenverlust der realen Untersuchung reproduziert, wohingegen nach der neu entwickelten Methode keine Fehler aufgetreten sind und

Figure 1.11: Request form: Description of the new study [3]

Chapter 2

Overview

As previously seen, it cannot be guaranteed that the RPM-system sends its breathing signal in a reliable way. This can cause data loss while doing a CT-scan. Therefore it was decided that the RPM-system's breathing signal is skipped. Instead, a separate external device called Trigger-Box sends a periodic breathing signal to the CT device. This assures that there is always a signal and data loss is prevented. The frequency of the periodic breathing signal is aligned to the patient's breath rate, which makes it easier to adjust this signal in a second step after the CT-scan.

With this setup a CT-scan can be performed while the Trigger-Box takes care of data loss prevention. In the meantime the respiration curve is still recorded by the RPM Gating System. After finishing the scan the Trigger-Boxes' signal needs to be correctly adjusted to the patients real respiration curve. The patient may have breathed slightly faster or slower than expected so the external breathing signal and real breath rate are mismatching.

Reconstruction would still work but the correct assignment of the different phases fails and results in several artefacts in the CT data. More artefacts mean a more complicated planning procedure for the radiotherapy. Therefore it is advisable to adjust the breathing signal so that every phase of the respiration can be reconstructed as exact as possible. The algorithm for calculating the best breathing signal adjustment is described in detail in Chapter 5.

The calculation of the correct breathing signal is based on the patient's respiration curve. Therefore it is necessary to use exactly the timespan of the respiration curve where the CT-scan was running. To do so it is necessary to find a common point in time for aligning CT-scan and respiration curve by time. This point in time is the end of the scanning. This means that the RPM-system's recording needs to be stopped exactly at the moment when the CT-scan is over. Varian did not include the possibility to stop the recording with the end of the scan. Therefore the stopping needs to be done by a mouse click.

As stopping by hand may result in uncertainty, a second device was developed in order to stop the recording automatically, exactly at the moment when the CT-scan stops. Due to the fact that a computer tomographic device is a medical system and must not be manipulated, external processing must be done to figure out the end of the CT-scan. The only signal that can be accessed from the outside is the warning light during active roentgen radiation. This lamp turns on when the CT-scan starts and switches off at the end of the scanning procedure. When the lamp goes out a mouse click is sent to the RPM Gating System and the recording stops.

With the knowledge of the total scan time, the desired part of the respiration curve can be extracted and further processed. After calculating the correct breathing signal the Trigger-Boxes' previously sent signal is adjusted and the reconstruction can be started.

Chapter 3

Hardware & Components

3.1 Trigger-Box

As mentioned in Chapter 2, the system for a better data collection for the scheduling of a radiotherapy needs to periodically send a breathing signal to the CT to prevent data losses. This breathing signal is a TTL signal with a 500ms high time. The signal is sent by the Trigger-Box that is operated by the doctors and other clinical personnel. Therefore it has to comply with several conditions.

3.1.1 Requirements

- HMI: keypad and graphical interface for better adjustment of the breathing signal period
- easy and clear to use
- stable
- connected to the CT via a Coax cable
- portable and encased in a robust housing
- shall be activated and deactivated manually
- easy to manufacture another time
- continuous operation over time without interruption

3.1.2 Printed Circuit Board

To comply with all the requirements in Section 3.1.1 it was necessary to create a new printed circuit board (PCB) for the implementation. The heart of the PCB is a 8-bit microcontroller ATmega32 from Microchip [11]. This device was chosen due

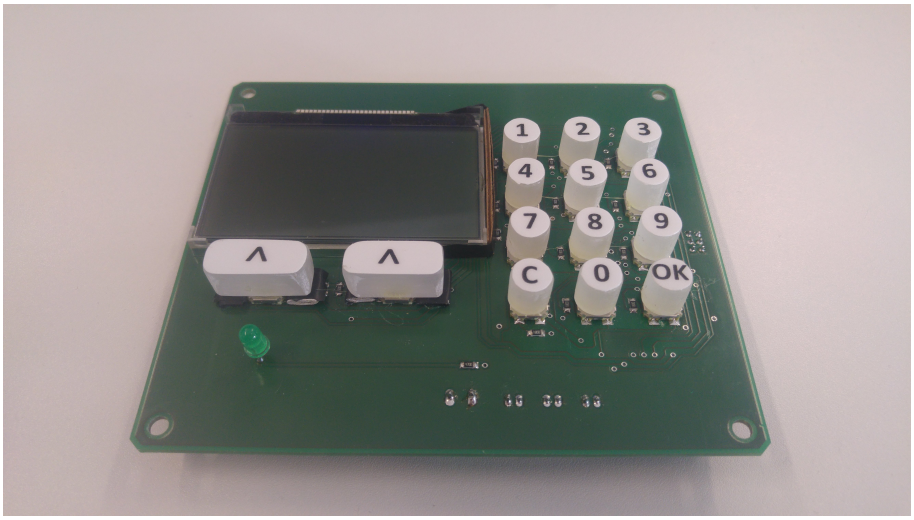


Figure 3.1: Trigger-Box

to its small dimensions and because it has enough I/O's for this kind of application.

Besides the microcontroller there is also a keypad on the PCB. This allows the doctor to adjust the breathing signal's period. In order to see and check the entered values, a graphical Liquid Crystal Display with 128 x 64 pixels was added to the PCB. Furthermore, two buttons were implemented to navigate trough the states of the Trigger-Box. There are also some other optical indicators for a better understanding of the Trigger-Box.

3.1.3 Microcontroller

The ATmega32 from Microchip comes in a 44-pin TQFP package. It has a 32 kilobyte program memory which is enough to store the firmware. Due to the fact that a graphical display was chosen, some RAM is needed to store the state of every pixel on the display. The microcontroller has a 2048 Bytes RAM which is two times the needed size.

The microcontroller runs with an external crystal with a frequency of 8 MHz. This allows the microcontroller to run on a very short time basis which results in a more precise breathing signal generation.

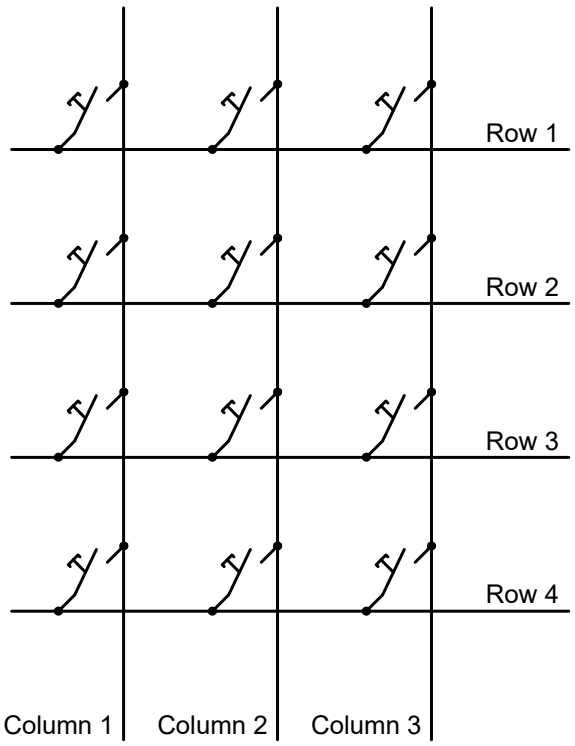


Figure 3.2: Principle of a keypad matrix with m = 4 rows and n = 3 columns.

3.1.4 Human Machine Interface

Keypad

The keypad consists of twelve buttons. It would be a big overhead to query every button separately. Therefore they were arranged in a 4x3 matrix as shown in Figure 3.2. A matrix only needs *m+n* data lines to check *m*n* buttons. This makes it possible to use only seven data lines for the twelve buttons: one for every column and one for every row.

When pressed, each button connects the row, in which he is aligned, with the corresponding column. This setup allows to reduce the data lines from twelve to seven. The drawback is, that it is no longer possible to directly detect, which button was pressed. An subsequent processing is a must to calculate the pressed button, which is described in Section 4.1.1.

All the tactile switches have built in LED's to illuminate them to signal a requested input. On top of the switches there are cylinders made out of translucent perspex with according labels on them. The translucent perspex ensures that there is an uniform illumination of the button for a better experience for the user.

Liquid Crystal Display

As a graphical interface a graphical Liquid Crystal Display (LCD) with 128 x 64 pixels and backlight lighting was chosen. The driver that controls the display ist the *ST7565R*. This driver can be connected the microcontroller via 8-bit parallel and 4 line serial interface (SPI-4). The slower serial interface was chosen due to fewer used data lines [14]. To draw figures on the display, the microcontroller needs a buffer with the same amount of bit as the LCD has pixels on its screen. Every bit in the buffer stands for a pixel. These bits are manipulated and afterwards sent to the display and its driver.

3.2 Automatic Recording Stopping

The weakness of manually stopping the recording of the patient's respiration curve is corrected by a developed device called Automatic Recording Stopping. The task of this device is to send a mouse click to the Varian PC when the light for active roentgen radiation goes out.

The device is separated into two parts. The first part is responsible for detecting whether the light for active roentgen radiation is on or not. This information is sent to the second part of the Automatic Recording Stopping device. This part processes the information about the light source and in case the light switches off, a mouse click is sent to the Varian PC via USB. Both parts have the size of an usual USB key.

3.2.1 Light Detection

The light detection is done by a photodiode. A photodiode is a device that converts visible light into electrical current. In this case it is the BP104 photodiode from Vishay.

The photodiode is operated in the reverse direction. The more incidence of light, the more current can flow in reverse direction. Running trough a load resistance, this current can create an output voltage depending on the amount of incoming light. The brighter the light source the higher the output voltage.

A comparator compares this output voltage with an adjustable reference voltage to determine whether the light source is switched on or off. The reference voltage is adjusted with a potentiometer. When the photodiode's output voltage exceeds the reference voltage, the output of the comparator is logical high - otherwise it is logical low. Additionally, the output of the comparator is negated to create a second data line which ensures that the Automatic Recording Detection is less prone to error.

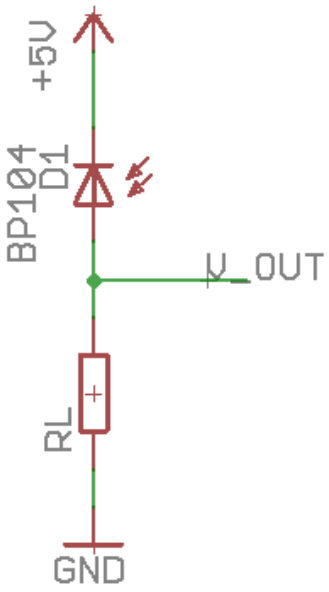


Figure 3.3: Principle of a phodiode with load resistance.

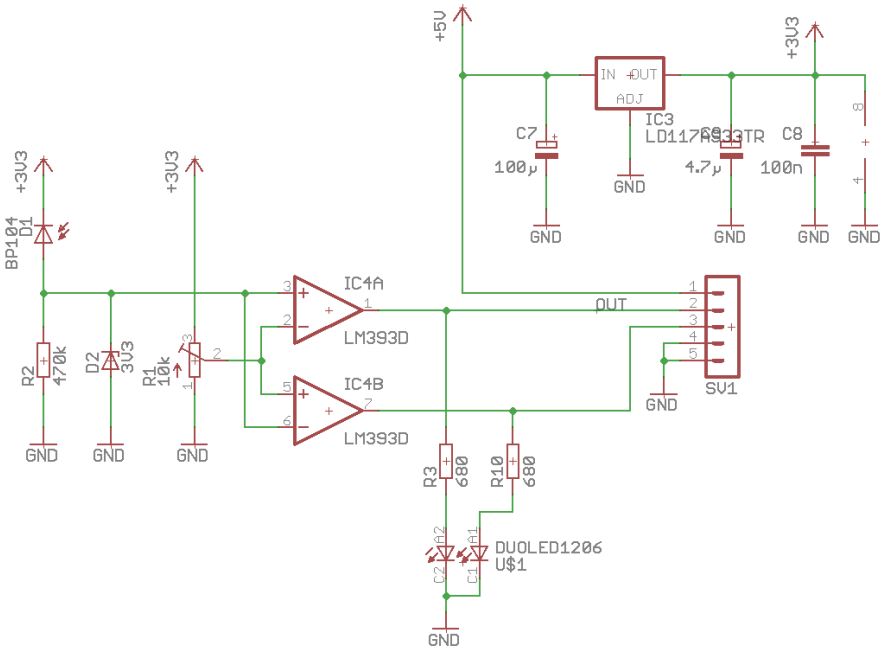


Figure 3.4: Schematics of the light detection part.

3.2.2 Mouse Click

The second part is responsible for sending a mouse click to the Varian PC. This task is performed by a microcontroller that is mounted on a PCB and connected to the PC via USB. The chosen microcontroller is a ATmega8U2 because of its very small dimensions and integrated USB controller. It has 32 pins which is more than enough for this kind of application. The µC processes the information of the two incoming data lines from the Light Detection part and sends the mouse click to the PC. The principle of the USB interface and firmware implementation can be found in Chapter 4.

Chapter 4

Software Implementation

Both microcontrollers described in Chapter 3 need a firmware to operate as desired. The firmware is written in *C* and the chosen IDE is Microchips' Atmel Studio 7.0.

4.1 Trigger-Box

The 8-bit microcontroller ATmega32 is programmed to behave like a finite state machine (FSM). A FSM is a device that has a finite number of states it can be in. Depending on the input and actions in the past, the device can switch from one state to another. In this system there are three possible states: *IDLE, RUN* and *SETTINGS*.

- After start-up the machine is in IDLE state and waits for an input. Depending on the input it changes to one of the other states.
- In RUN state the breathing signal is sent to the CT. After stopping this state the software is in the initial state again.
- The SETTINGS state waits for an input from the keyboard to change the trigger period. While entering the breathing signal's period the state remains the same. When the entered period is confirmed or discarded, the next state is the IDLE state.

4.1.1 Keypad

Due to the fact that the keypad only has seven data lines, some extra processing is needed. To detect and determine a pressed button in a matrix like this, the following steps are performed. All buttons have an active low behaviour. This means that the button's "output signal" is high on idle state and low when pressed.

1. Declare the data lines for every column as output and connect it to low level.

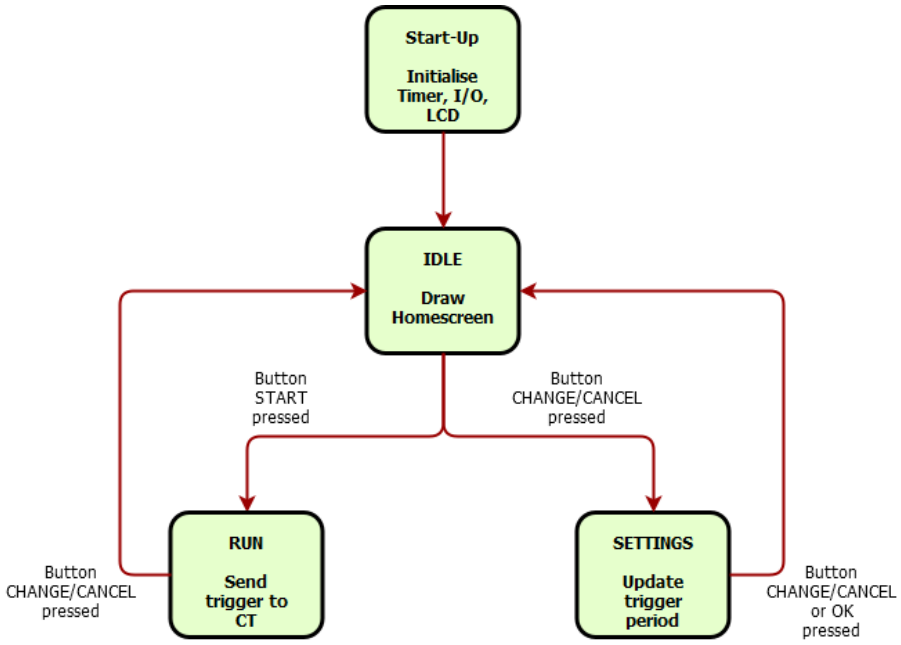


Figure 4.1: State diagram of the microcontrollers' firmware of the Trigger-Box.

2. Declare the data lines for every row as input and turn the internal pull-up resistors of the microcontroller on.

3. Now poll all four rows for a low level. If there is a low level on a input data line, a button in the corresponding row is pressed.

4. When a button press is detected, all rows and columns change their input/output behaviour: All rows now become outputs and all columns become inputs with their pull-up resistors on. All outputs are connected to high level, except for the one in whose row the button press was detected. This means that only buttons in this row are now queried.

5. The pressed button is located in the column where the corresponding data line is on low level.

6. Restart with step 1.

As seen in the previous enumeration, the algorithm for locating the pressed button is simple to undertake [12]. It should also be mentioned that this algorithm is not designed to detect two or more buttons at the same time as it is not necessary in this implementation. Only the first detected button is evaluated and the rest is discarded.

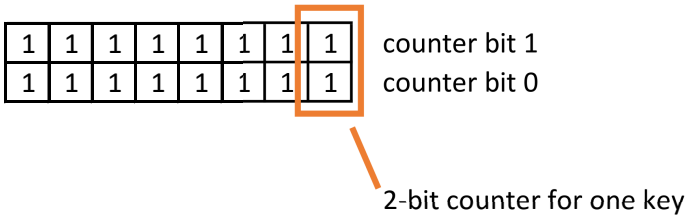


Figure 4.2: Vector of 2-bit counters for key debouncing.

4.1.2 Debouncing

It is not enough to just poll for a low level on the input to detect a keystroke. Switches and buttons tend to bounce when they are turned on or off. This means that they switch on and off repeatedly for a short amount of time. This is a not desired behaviour and can lead to mistakenly detect more keystrokes than actually happened. This is where the debouncing algorithm comes in [13].

A button can have four states:

- the key was not pressed and is not pressed
- the key was not pressed and is now pressed
- the key was pressed and is still pressed
- the key was pressed and is not pressed any more

In this implementation all the keys are polled with a frequency of 100Hz or every 10ms. It was defined that a keystroke is detected when a key is on the same level for four consecutive polling intervals. This means that a keystroke is detected after 40ms. Every button has a 2-bit timer assigned to it. This timer is initialised to its maximum value: three. When the first level-change is recognised, the counter is decremented. In the next polling interval the button state is queried again. If the button state is on the same level as before, the counter is decremented again. If the level is not the same, the counter is reset to the initial value. In case, the data line level of the button is on the same level for four consecutive polling intervals, the counter underflows from zero to the value three. A button press and its new state is correctly recognised.

This is done for every row in the keypad and the two keys beneath the display. As it would be very time consuming and also memory-inefficient to implement a separate counter variable for every input, two timer vectors are used. These two vectors allow to create several 2-bit counters with just two variables. The processing is done with byte-wise bit manipulation, so the whole calculations have to be done only once for all inputs and timers at the same time [13].

4.1.3 Timing

To have a precise timing, the system works on a time basis of 1 ms. This is achieved with the 10-bit timer of the microcontroller. This timer can be pre-set to a specific value and on every overflow it raises an interrupt. In this implementation a 8 MHz crystal is used. With no pre-scaling the timer increments every 125 ns. This means that the timer counter increments 8000 times per millisecond. Therefore the 10-bit counter has to be pre-set to its maximum decreased by 8000: $2^{10} - 8000 = 57535$. In the interrupt service routine (ISR) the timer counter is reset again to its initial value, and the timer is restarted after the interrupt.

As the execution of the ISR takes some time, the time basis is 1 ms plus the amount of cycles to go through the code of the ISR. Therefore the amount of timer-ticks until overflow, in this case it is 8000, is reduced by exactly the amount of cycles needed by the ISR.

4.2 Automatic Recording Stopping

The firmware of the Automatic Recording Stopping is continuously checking whether the output signal of the comparator of the Light Detection part has a falling edge. Because there is also a data line with the inverted signal of the comparator output, there is also a checking for a rising edge on the the second data line.

In case the falling respectively rising edge is acquired, a mouse click is sent to the Varian PC. To do so, a working USB connection is needed.

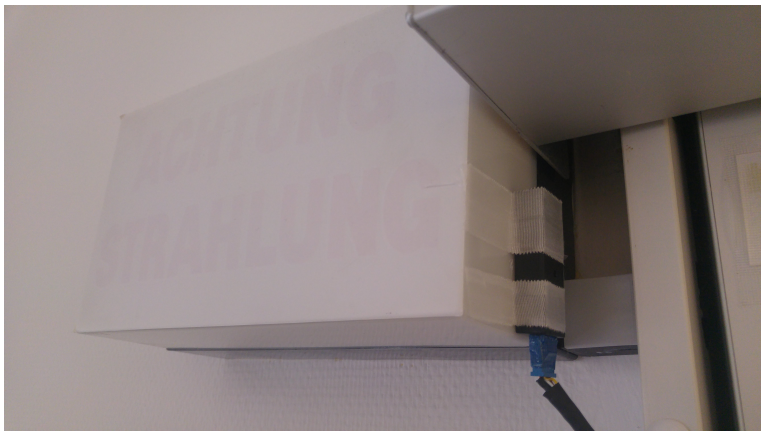


Figure 4.3: Light detection part attached to the warning light for active roentgen radiation

4.2.1 USB Connection

The Universal Serial Bus (USB) is an external Interface for a lot of devices that are connected to a computer. It can work with a big number of different types of

Figure 4.4: USB part of the Automatic Recording Stopping Device

devices. The most common are Mouses, Keyboards, Printers, Cameras and many more.

One big advantage of the USB interface is the possibility for hot-plugging. This means that the external device can be connected and removed while the PC is running. When a new device is connected to the computer, it is identified by the USB-Hostadapter of the PC. This adapter is also responsible for loading the appropriate driver and configuration. Some devices work by just plugging it into the computer. The operating system automatically installs the needed driver. But when the device is not known the operating system asks the user for a driver. Here the user needs to manually install the device's driver to make it work properly [8].

The Automatic Recording Stopping just needs to send a mouse click. Therefore it makes sense that the device identifies itself as a mouse. Mouse and Keyboard are Human Interface Devices (HID) and are used for interaction between user and computer. Every operating system already has a HID-driver. Therefore it is not needed to install a separate driver for the Automatic Recording Stopping.

Chapter 5

Breathing Signal Calculation

When the 4DCT is finished, the CT-software begins with the processing of the collected data. Depending on the breathing signal, generated by the Trigger-Box, the CT processes the collected images in a different way. In case the patient's breath rate was exactly the same as the breathing signal from the Trigger-Box, the reconstruction works very well without any artefacts.

This happens only in very rare cases. Therefore the breathing signal needs to be adjusted in a seconds step after finishing the CT-scan to achieve the best possible reconstruction without artefacts. This means that the timings of the individual triggers of the breathing signal are modified in a second step. In this adjusting procedure every breathing irregularity and couching event is taken into account to generate an optimal breathing signal for a better reconstruction.

5.1 Respiration Curve

In order to calculate an optimal breathing signal, the recorded respiration of the patients is needed. Even when the RPM system is not sending any breathing signal, it still is recording the patient's respiration curve. This curve can simply be exported. The format of the exported respiration curve file is *.vxp*.

This VXP file contains a header (see figure 5.1) with information about the patient, date, some CRC data and several timing information. The respiration curve data itself starts immediately after the header with information about the amplitude, phase, timestamp and some flags [6].

5.2 Algorithm to generate an optimal breathing signal

After successfully exporting the respiration curve, the algorithm can be applied.

```
[Header]
CRC=60262
Version=1.6
Data_layout=amplitude,phase,timestamp,validflag,ttlin,mark,ttlout
Patient_ID=xxxxxx
Date=02-23-2018
Total_study_time=225.385
Samples_per_second=25
Scale_factor=10.0
[Data]
-0.0874,5.6256,77942,0,0,,0
-0.1817,5.6987,77997,0,0,,0
-0.1817,5.7718,78022,0,0,,0
-0.2163,5.8448,78062,0,0,,0
-0.2434,5.9179,78102,0,0,,0
```

Figure 5.1: Header of a VXP file

The goal of the algorithm is to generate an optimal breathing signal for every respiration phase. This means that the breathing signal is different for every phase, which results in more work to edit it, but the reconstruction is delivering better results.

Due to the fact that it is assumed that the computer tomographic device is internally working with an ideal sinus between two triggers of the breathing signal, the algorithm needs to calculate the optimal timestamps of the triggers that the amplitude of the desired respiration phase is on target for reconstruction. When the 50% phase should be reconstructed, it is wanted that the lowest amplitude of the breathing signal is exactly at the lowest point of the ideal sinus. The two maxima (trigger) of the sinus need to be placed that this is fulfilled but also is still working for previous and subsequent breathing cycles.

First of all, the header needs to be read in to know the sample rate of the respiration curve. As previously said, the only common point in time is the end point of the CT-scan. With the knowledge of the length of the CT-scan, the desired section of the original respiration curve is known and be "cut out". The algorithm for breathing signal calculation is applied on this specific part of the curve.

When the exact part of the respiration curve is known, it is normalised and smoothed to eliminate noise from recording the curve. After that, all the peaks of the curve, minima and maxima, need to be determined. This is done by looking for a sign change in the first derivative. In order to prevent false positives the curve is checked for saddle points respectively "small hills" that are not an absolute minimum or maximum of the respiration curve. If there is a false minima or maxima in the range of a saddle point, the incorrectly detected peak is removed.

There is also another criteria for peak detection. To have a clear separation, a maxima is only detected and stored, when its amplitude is higher than 0.7 of the normalised respiration curve. Analog to this, the minima must be lower than 0.3.

It is possible and quite common that there is not always a minimum and maxi-

mum on an alternating basis. This comes from the not optimal shape of the patient's respiration curve. Some peaks may have bumps and therefore two or more very close maxima respectively minima are detected. This effect could be minimised by more smoothing but the shape of the original curve would be changed significantly.

In the next step the unnecessary peaks are deleted or missing ones are added respectively. For example if there is no minimum between two maxima it is necessary to check whether a minimum is missing or one maxima is detected by mistake.

Therefore it is checked if there is a point that can possibly be a minimum (amplitude lower than 0.3) - looking at the case of two consecutively maxima. If there are multiple possible minima between the two maxima, the one with the lowest amplitude is chosen. If there is no point that could be a minimum there is one maximum too much. In this case the time stamps of the two points are averaged so that only one maximum is left. The procedure is analog for searching possible maxima.

There is also another test case to detect very close minima and maxima. For example it cannot be that the patient's inspiration or expiration cycle is unnaturally short. Here, both maximum and minimum are deleted to maintain the alternating order of the peaks.

When all the previous steps are performed, all the minima and maxima are detected in a correct manner. The remaining step is to calculate the triggers of the breathing signal to have the desired respiration phase on target. The first fixed point is the first maximum of the respiration curve. The next fixed point is the point between the first maximum and the following maximum - with the amplitude the ideal cosine would have at the desired respiration phase. The cosine is defined when the starting point of the period and the amplitude after a certain time is known. Therefore it is no problem to calculate the endpoint of the cosine's period. This point is the next trigger of the breathing signal and the start point for the next breathing cycle and cosine. This is continued until the end of the desired part of the respiration curve.

Due to the fact that all respiration phases over 50% are on the second half of the cosine's period, the part for trigger calculation starts at the beginning of the respiration curve to have a more accurate interpolation. When the desired reconstruction phase is below 50% the cosine defining points are very close together which may result in some inaccuracies when calculating the endpoint of the period. Therefore for phases below 50% the whole trigger calculation part starts at the end of the respiration curve going forward.

A detailed description of the algorithm in Matlab Code can be found in Appendix A.

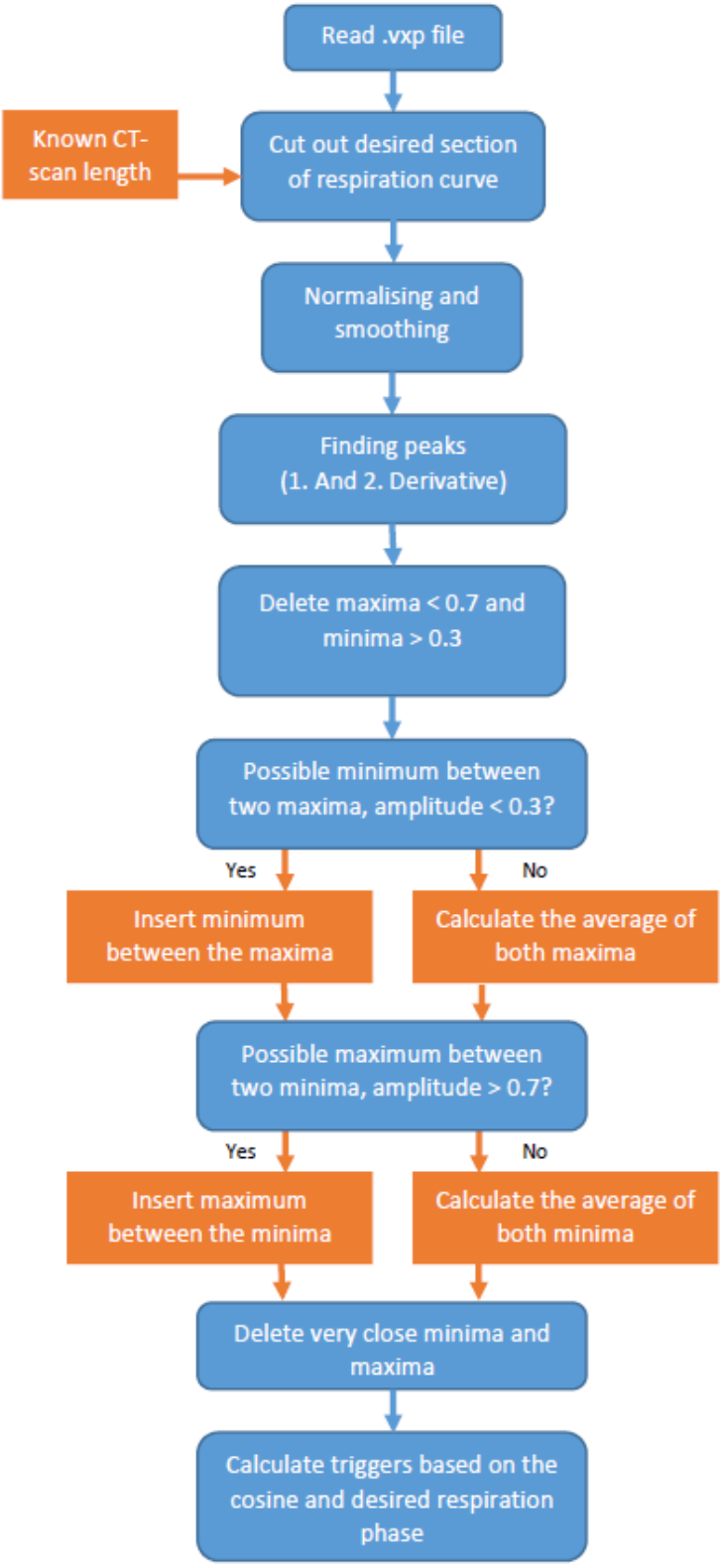


Figure 5.2: Flowchart of the algorithm to generate an optimal breathing signal

5.3 Graphical User Interface for Breathing Signal Generation

The Algorithm in section 5.2 is developed and tested in MATLAB. Again, to make the whole procedure more user friendly and usable for doctors and other clinical personnel, a GUI written in C# was developed. Here it is possible to search for a VXP file like in every other Windows Program. There is a Help section and by visually leading the user through the program flow the clinical personnel is able to work with this program.

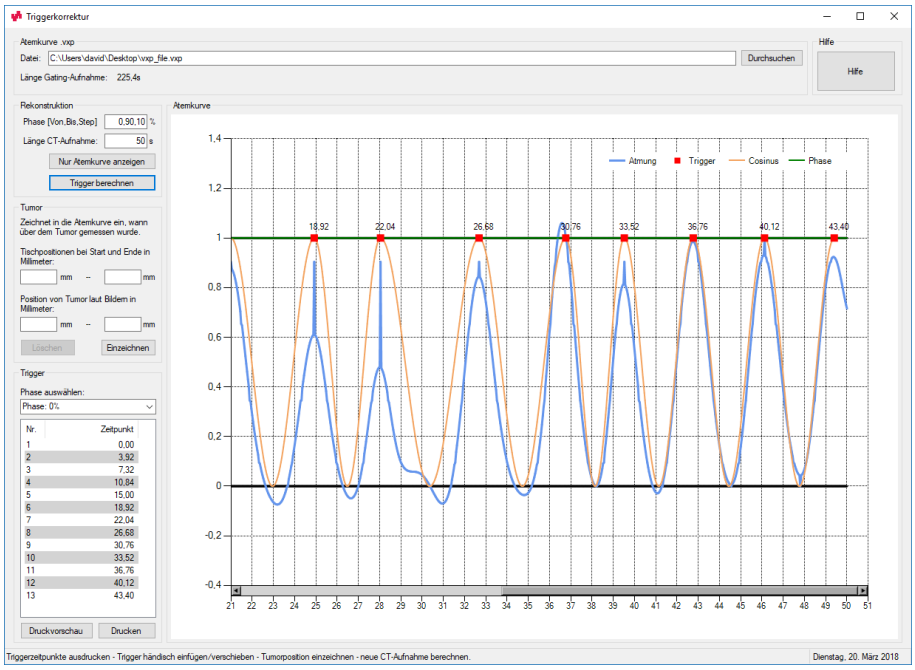


Figure 5.3: GUI used by doctors and other clinical personnel

The GUI offers an extra feature that allows the doctors to analyse the patient's respiration when the CT was scanning over the area of tumorous tissue. The doctors know the exact start position of the CT couch where the patient lies on and its end position. These positions are expressed in Z coordinates. Furthermore, after finishing the CT scan, the computer tomographic device does a quick reconstruction of the 50% phase. There it is possible to determine the location of the tumorous tissue. Every slice that has been reconstructed also contains the information about its Z coordinate in the CT's system of coordinates. Due to the fact that the movement of the table during scanning is constant to achieve an uniform helical shape, the movement of the table can be connected to the respiration curve by time. If the reconstruction shows that the scanning over the tumorous tissue was exactly in the middle between starting point and end point of the table movement, it can be assumed that the central part of the respiration curve shows the thorax movement

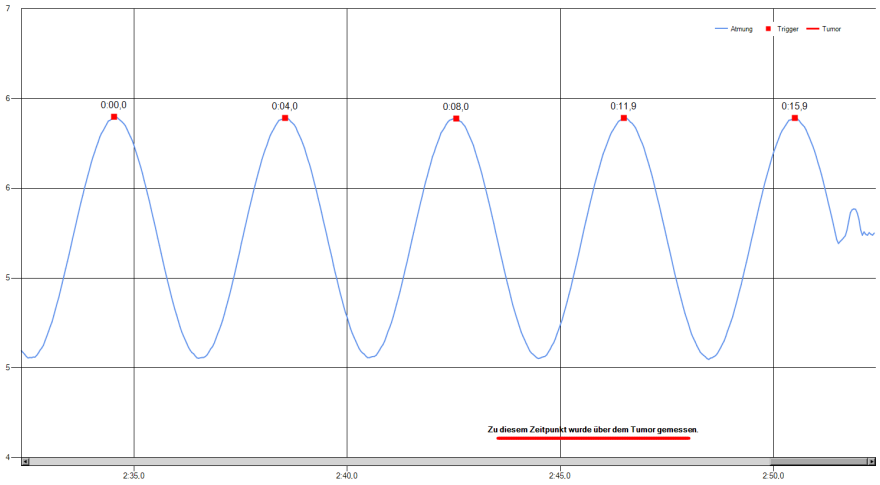


Figure 5.4: Visual representation of the time period while scanning over the tumorous tissue

while scanning over the tumorous tissue.

For other Z coordinates the timing of the concrete respiration cycle can be calculated analogous, percentage-wise.

Chapter 6

Testing and Results

The whole system was tested with the computed tomographic device, Toshiba Aquilion LB V.3, at the LKH-Univ.Klinikum Graz, Department of Therapeutic Radiology and Oncology. For all following test, the CIRS Thorax Phantom was used and the reconstruction is done on the basis of the instruction at the department for Therapeutic Radiology and Oncology. This means that the resulting reconstruction is done in steps of 10%, starting with 0% and a slice thickness of two millimetres.

After reconstruction, the data is exported to a graphical planning programme called Pinnacle from Philips. Here the gross tumor volume (GTV) for every phase and the resulting internal resulting volume (ITV) over all phases are computed.

6.1 Performed Tests

1. The first step was testing the Trigger-Box for its functionality. Here the breathing signal cable from the RPM system is disconnected and the Trigger-Box is connected to the CT. Several CT-scans were made with this setup to prove its functionality.

2. The following test was looking at the CT's behaviour with different breathing signals. The CIRS phantom was used to simulate an ideal respiration with sinusoidal movement. The sinus' period was four second with an amplitude of 20mm. In this scenario the optimal period of the breathing signal would be four seconds. But in order to find out more about the CT's behaviour, the breathing signal's period - sent from the Trigger-Box - was modified in 15 different tests starting from the minimal period of two seconds up to the maximum of six seconds.

3. Also the next texts were done with the CIRS Thorax Phantom. Here the respiration curve was not ideal any more. The period but also amplitude were changing but not dramatically. Overall it was a realistic respiration that can be seen in figure 6.1.

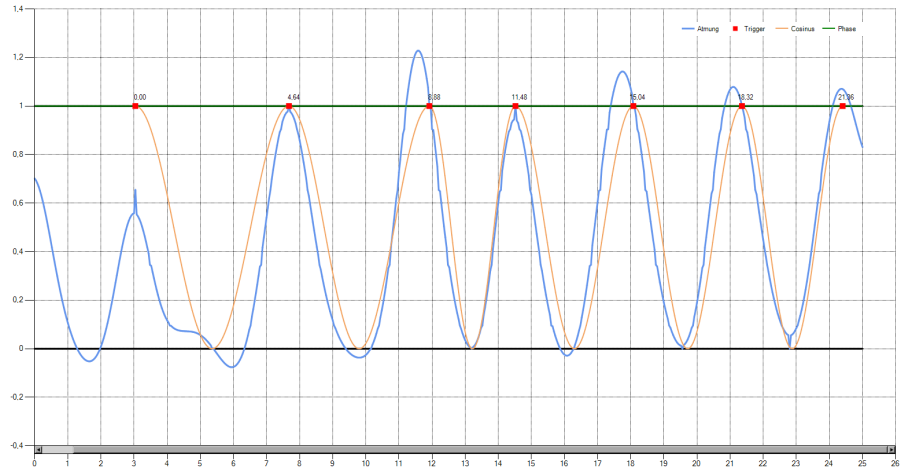


Figure 6.1: Realistic respiration curve with breathing signal calculation

4. One idea was that a high-frequency breathing signal should result in a very high sampling rate of the respiration curve. Therefore another test was made with a very bad respiration curve. There is a very long dropout when the 4DCT is scanning near the area of the simulated tumorous volume (see figure 6.2). Only while scanning at the exact position of the tumorous tissue there is a high breathing amplitude. When reconstructing, there should not be much phases where the tumour is visible in. But if the breathing signal is high-frequent, there should be more phases with information of the location and volume of the tumour. Therefore the test was done by sending an aligned breathing signal with the Trigger-Box and then editing it after the CT-scan. The first editing is done by the default-procedure at the LKH, the second is done with the newly developed algorithm and at the third reconstruction the triggers of the breathing signal are modified that their period is at the minimum of two seconds.

After getting some unexpected results in test number 4, tests regarding randomly adjusting the breathing signal were made. The following three tests are on the basis of an ideal sinus with a period of five seconds and an artificial short dropout while scanning near the simulated tumorous tissue, seen in figure 6.3

5. This test is divided into two parts. In the first part, the Trigger-Box was sending a breathing signal consistent to the respiration curve without any dropout. Two reconstructions were made: One with default breathing signal adjustments and the second was done with a breathing signal period of two seconds.

   In the second part, the Trigger-Box was sending a breathing signal with a period of two seconds. Also in this part, two reconstructions were made. One

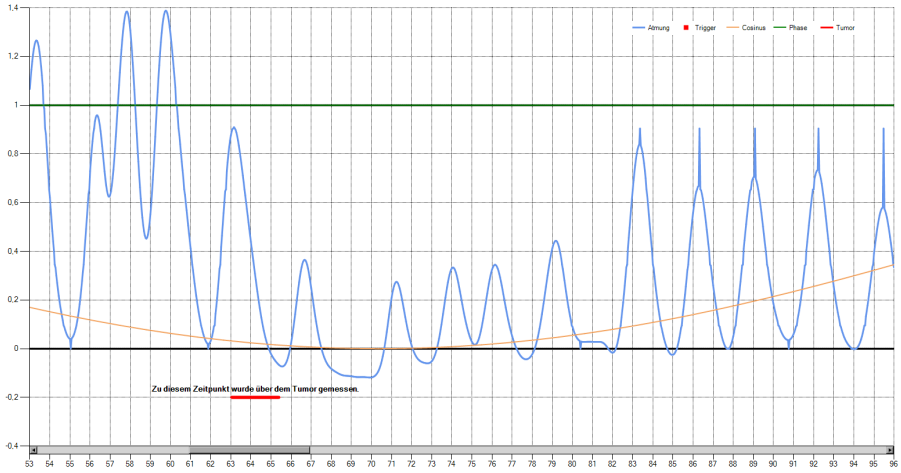


Figure 6.2: Big dropout while scanning near the location of the tumorous tissue

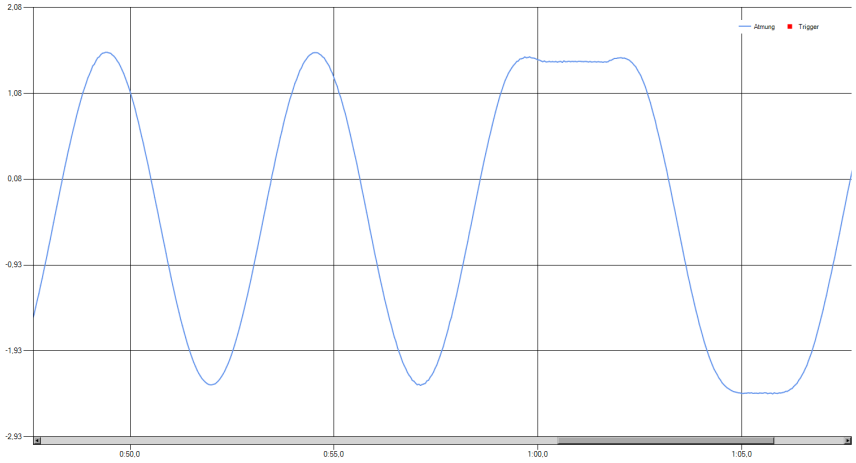


Figure 6.3: Ideal sinus with an artifical short dropout

with the original breathing signal from the Trigger-Box and the second was done after shifting every trigger 500ms - except the first one.

6. The next test was also splitted up into two parts. The goal of this test is to see how the reconstruction changes when the frequency of the breathing signal is doubled respectively halved.

   Therefore in the first part the Trigger-Box was sending a breathing signal with a period of five seconds - consistent to the respiration curve. The first reconstruction of this part was made on exactly this breathing signal. Then there was added a trigger between each pair of consecutive triggers. This results in a breathing signal with twice the original frequency for a second reconstruction.

   The second part of this test is the exact opposite of the first part. The Trigger-Box sends a breathing signal with a period of 2.5s even if the respiration curve's period is five seconds. The first reconstruction is done with the originally sent breathing signal. After that, every second trigger is deleted to obtain a period of five seconds which is consistent with the respiration.

7. The next measurement is divided into five reconstructions. Again, the Trigger-Box was sending a signal with a period of five seconds. Then the breathing signal was edited in five different ways:

   - All triggers except the first are moved
   - The whole breathing signal is shifted
   - Random triggers
   - All triggers except for the first and the last are deleted
   - All triggers are deleted

In order to have some comparison between different manufacturers of computed tomographic devices, a device from Philips was tested in Leoben. Only some general tests were made to get an idea of this device's behaviour.

6.2 Issues during testing

While carrying out the tests, there were some difficulties that needed to be handled. Not everything went as smoothly as expected.

Time was a critical factor for the tests. As the newly developed system may change the approach for radiotherapy planning, it was desired that the development is done as quickly as possible.

Another key factor while testing was the availability of the computer tomographic device. Usually it was possible to use this device only in the afternoon. Due to the fact that scanning and reconstructing takes a long time, only a few measurements can be done per day.

Especially when reconstructing the different phases separately, it takes a very long time. Performing a a 4DCT-scan with reconstruction can take up to three days of testing. For editing every phase's breathing signal individually it is necessary to wait until the reconstruction finishes in order to edit the breathing signal for the following phase. In the case of the Toshiba Aquilion LB V.3, combined with the scanning area of the thorax phantom, the whole procedure for reconstructing all ten phases takes about seven to eight hours.

It was also very difficult or better said not possible to reproduce one test several times. The timing between starting the thorax phantom, starting the Trigger-Box and starting the CT-scan is very hard to handle. As everything must be done manually, it is nearly impossible to achieve the exact same result two times. Therefore limited comparability is given.

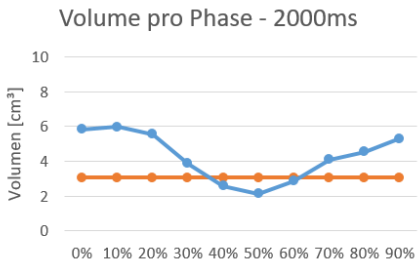
6.3 Testing Results

The testing results were not as expected. It was discovered that the Toshiba LB V.3 does not react to a manually edited breathing signal. This means that the correction of the original breathing signal is not influencing the reconstruction. The consequences are that the initial goal of this Master's Thesis could not be achieved but also that the scanning workflow at the LKH-Univ.Klinikum Graz, Department of Therapeutic Radiology and Oncology was changed due to the misbehaviour of the CT.

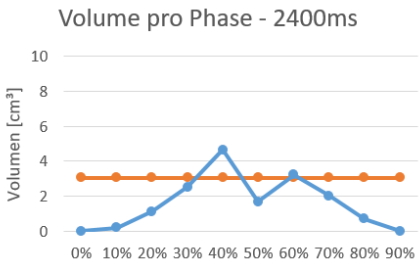
1. The functionality of the Trigger-Box should have been proved. It was used in all mentioned tests. It never showed any failures or misbehaviour. Therefore it can be states as a stable device and it was already used to make the first Trigger-Box-4DCT with a patient. Everything went smoothly and as expected.

2. In the next test, the breathing signal - sent from the Trigger-Box - had 15 different periods. The respiration curve had a period of four seconds. The following tables show the resulting volumes of the simulated tumour by phase. In the end there is a comparison of the total ITV, depending on the breathing signal's period.

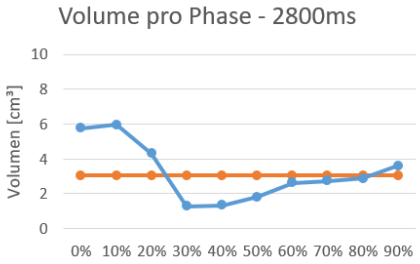
   In figure 6.4 can be seen that the tumour volume is varying over the different phases and is not staying constant. Another observation can be made that the closer the Trigger-Boxes' breathing signal period to the ideal period, the less Standard Deviation is occurring. A high standard deviation stands for a lot



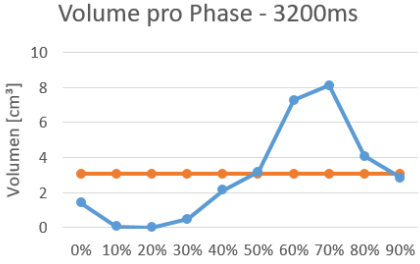
(a) 2000ms



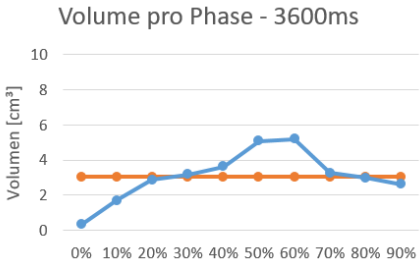
(b) 2400ms



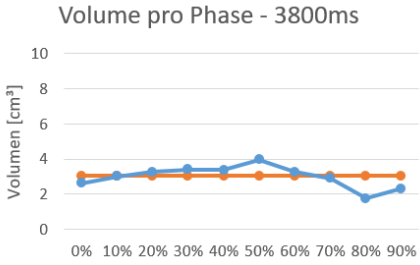
(c) 2800ms



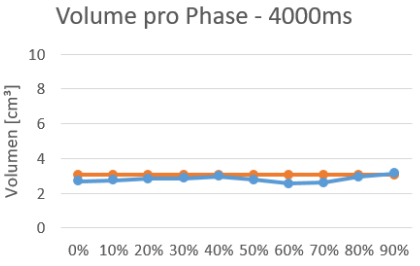
(d) 3200ms



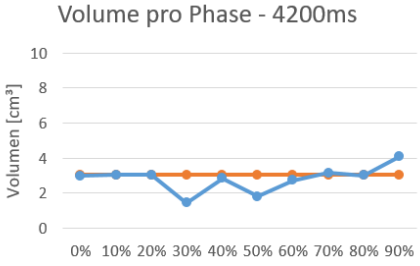
(e) 3600ms



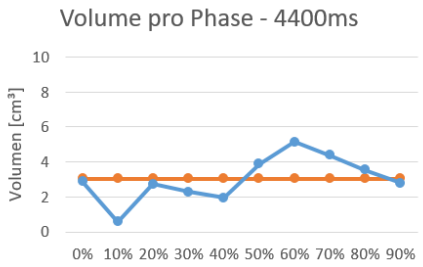
(f) 3800ms



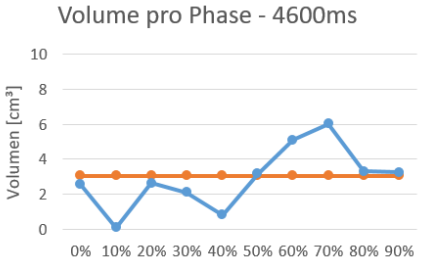
(g) 4000ms



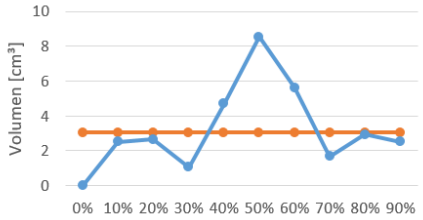
(h) 4200ms



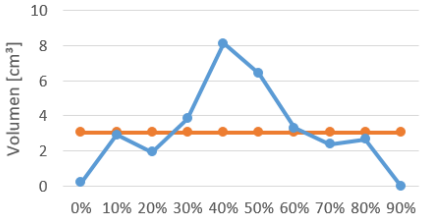
(i) 4400ms



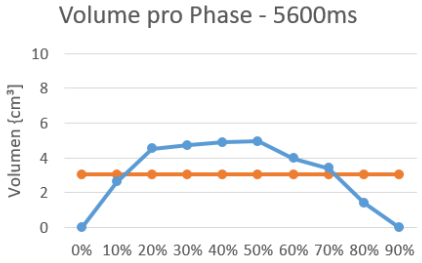
(j) 4600ms



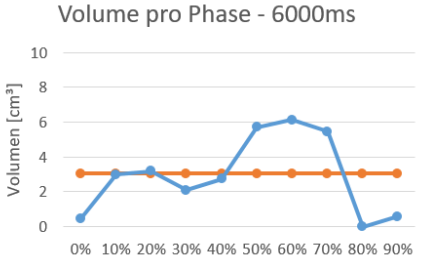
(k) 4800ms



(l) 5200ms



(m) 5600ms



(n) 6000ms

Figure 6.4: Volumes per phase - 2000ms to 6000ms

of artefacts in the reconstructions. This means that the tumour does not look like an entire piece, instead it is cut into several pieces.

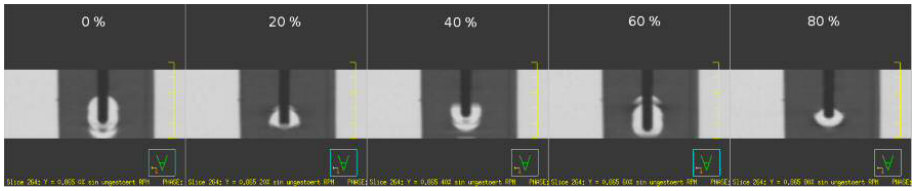


Figure 6.5: 4DCT-scan of the Thorax Phantom with artefacts [10]

The many artefacts are not pleasant to handle while planning, but in the end all the pieces and artefacts are summed up so that the ITV stays the same for all 15 test runs, which is observable in figure 6.6. Therefore it can be said, that the breathing signal is responsible for the quality of the reconstruction of the individual phases, but it has no impact on the resulting ITV. The testing series resulted in a coefficient of variation of up to 96% in the separate volumes per phase within one 4DCT-scan. Nevertheless the total volume of the different scans results in a standard deviation of 0.315 cm^3 (theoretical volume: 12.72 cm^3) and a coefficient of variation of 2.5%.

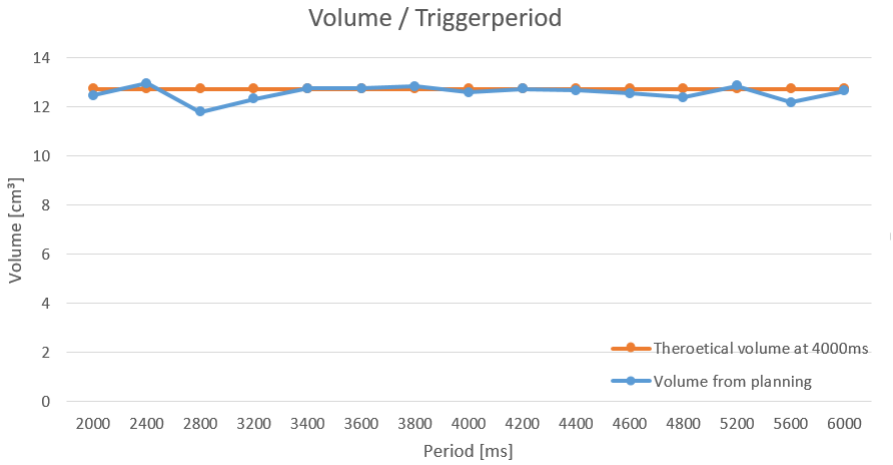


Figure 6.6: Test 2 comparison: Volume per phase with different breathing signal from the Trigger-Box

3. In test number three, the Trigger-Box sent the breathing signal only once and after that there were four reconstruction with a manually edited breathing signal in software. The results can be seen in figure 6.7.

   It can be seen that the volume changes over the different phases. But the most important thing that can be observed is that the separate phases are not reconstructed in a different way, even if the breathing signal was edited in software after the CT-scan.

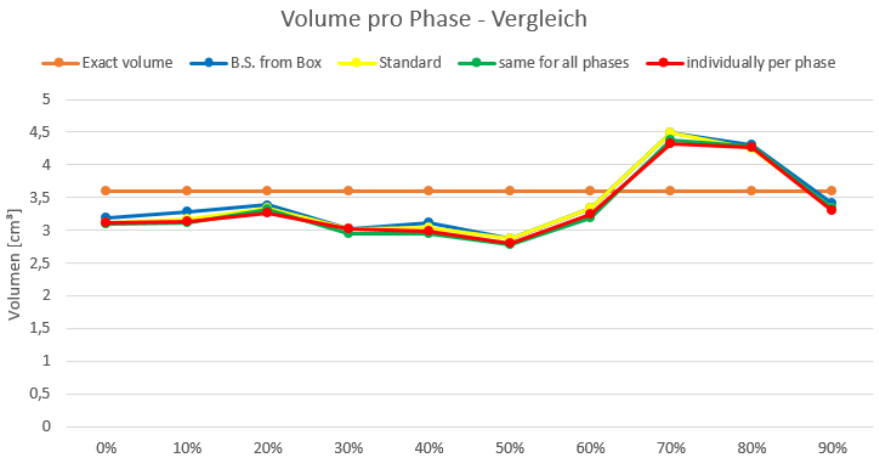


Figure 6.7: Test 3 comparison: Volume per phase with different breathing signal changed in software

4. In principle, the fourth test has the same outcome as test number three. The volume changed with the different phases. But once again, the separate phases do not differ after reconstruction, even if the breathing signal was edited in software after the CT-scan (see figure 6.8).

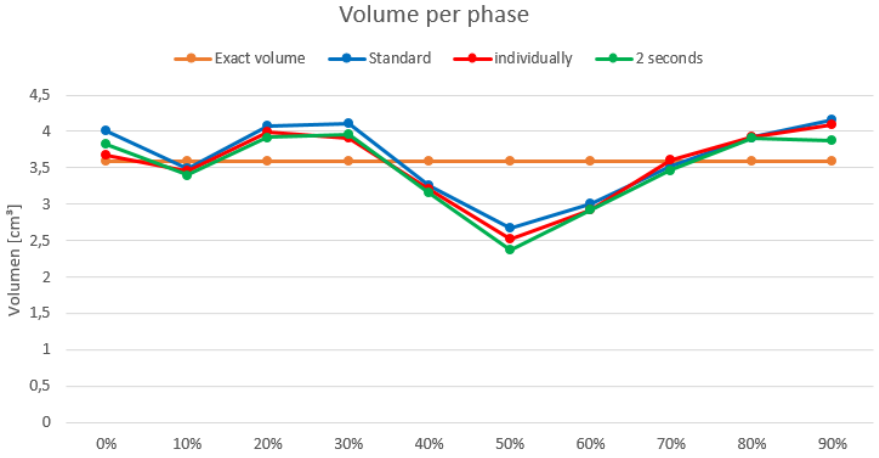


Figure 6.8: Test 4 comparison: Volume per phase with different breathing signal changed in software

5. Test 5, 6 and 7 also have the same kind of outcome. The phases differ between each other. But, expectedly, the separate phases do not change with an edited breathing signal software wise.

6. At last the test in Leoben showed that their computer tomographic device does react to different breathing signals. It is not possible to connect the

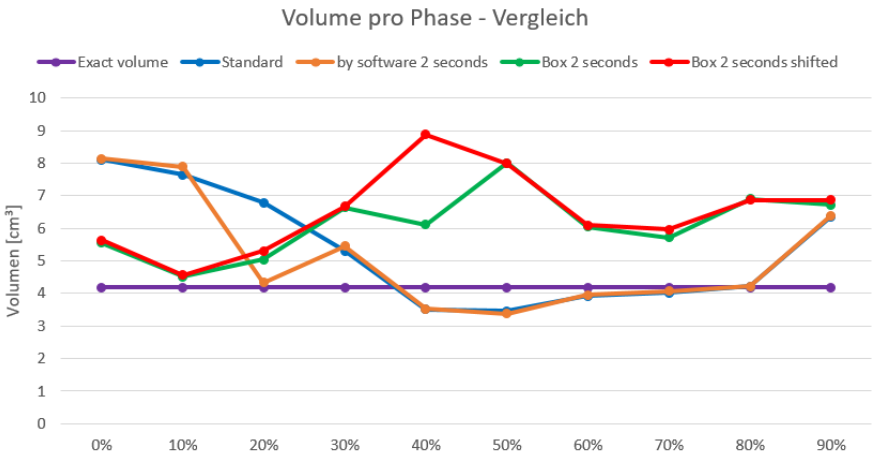


Figure 6.9: Test 5 comparison: Volume per phase with different breathing signal changed in software

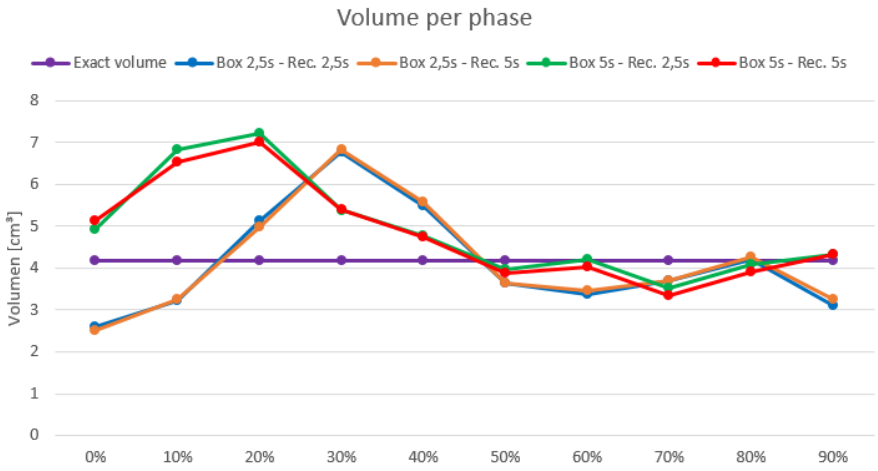


Figure 6.10: Test 6 comparison: Volume per phase with different breathing signal changed in software

Trigger-Box to the CT in Leoben. Therefore an optimal respiration curve was simulated by the CIRS dynamical thorax phantom. This ensures that the Varian RPM-system sends a periodical breathing signal to the CT and no data is lost. After the first reconstruction the original breathing signal was edited. The CT in Graz would not react to this kind of modification but in contrast to that, the Philips CT in Leoben did put out a different reconstruction than with the original breathing signal. This means that a different breathing signal, even only modified in software after the scan, would result in a different reconstruction and the developed method could be applied there.

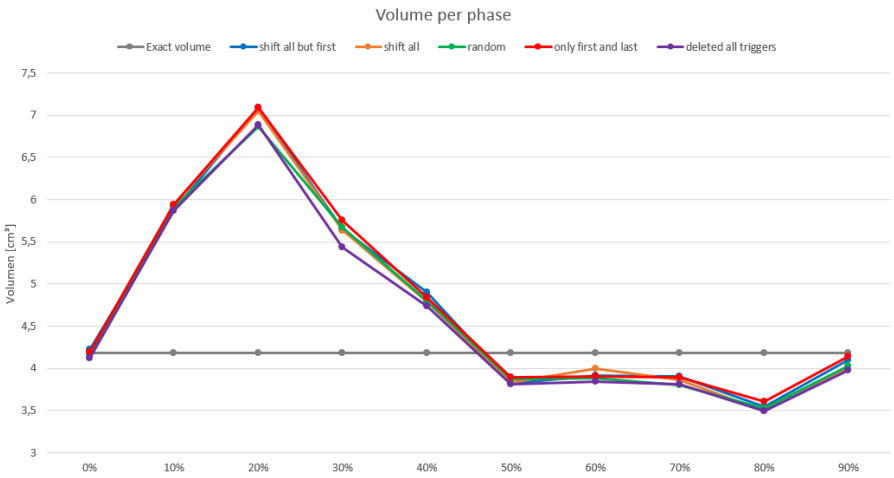


Figure 6.11: Test 7 comparison: Volume per phase with different breathing signal changed in software

After these results, the scanning workflow at the LKH-Univ.Klinikum Graz, Department of Therapeutic Radiology and Oncology was changed in order to prevent data losses. In figure 6.12 a real patient respiration curve can be seen. The Varian RPM-system would have sent triggers like marked in red. The big dropout leads to a time gap of more than ten seconds between the two triggers. This is more than the permissible time period of six seconds between two triggers. A data loss would occur. In contrast to that, the Trigger-Box sends triggers with a constant time gap between each other and prevents data losses. In this case the reconstruction of the separate breathing phases is not optimal but this has no impact on the total volume of the tumorous tissue and a second 4DCT-scan was avoided.

This method was successfully applied to six patients and no data loss did occur.

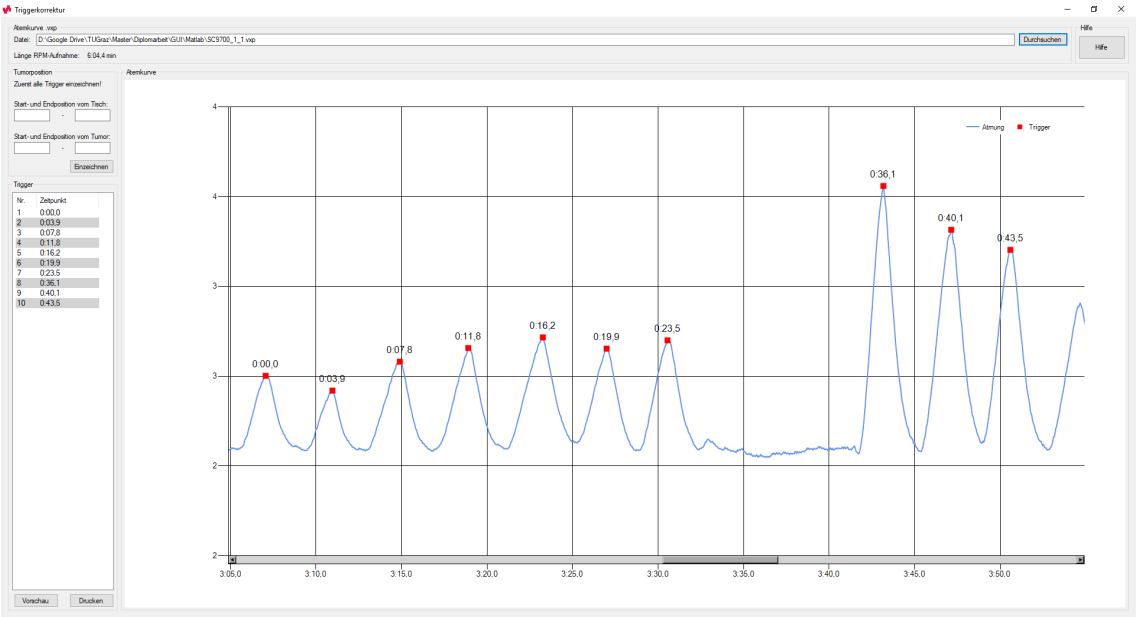


Figure 6.12: Real patient respiration curve that would have led to data losses

Chapter 7

Conclusion

It can be seen that the reconstruction does not change, when the breathing signal is edited in software after the CT-scan. Therefore the only crucial factor responsible for a good reconstruction is the breathing signal sent from the RPM System or Trigger-Box. Until now there were some breathing signal adjustments in software by the doctors. Looking at the performed test and their results it can be said, that these adjustments are unnecessary as they have no impact in the reconstruction.
These results were not expected. Therefore the LKH-Univ.Klinikum Graz, Department of Therapeutic Radiology and Oncology needs to make tradeoffs between a maybe better reconstruction with the RPM System's breathing signal, but possible data loss and a reconstruction with maybe more artefacts but without any data loss in any case.
The test in Leoben showed and approved that the device in Graz does not react to different breathing signals and the one in Leoben does. This means that the newly developed algorithm could be tested and further improved there.

7.1 Future Work

As said in chapter 6.1 there was a quick test in Leoben to check for some differences in reconstruction. The computer tomographic device at Leoben is from another manufacturer and not as old as the one in Graz. The new device does not have the problem of data losses any more. The surprising part of the test was that the reconstruction is not as good as expected. The applied curve was an ideal sinus with a short dropout. Some artefacts were expected but the resulting reconstruction was not usable. The were a lot more artefacts than expected.

Furthermore, the newly developed algorithm was applied to the reconstruction. It can be seen that the editing of the breathing signal has an impact on the reconstruction. In future work, it could be tried to improve the algorithm for a better reconstruction at the CT-device in Leoben. The exact approach is unknown as there was not enough time to get a better understanding of the the computer tomographic device in Leoben.

Appendix A

Matlab Snippets

```
% Einlesen
fin = fopen('file.vxp');
for k = 1:10 %header sepereat behandeln
    b = fgetl(fin);
    if k == 8
        s = strfind(b,'=');
        smp = b(s+1:end); %samples/second auslesen
        smp = regexprep(smp,' ',''); %leerzeichen löschen
        smp = str2double(smp); %in wert umwandeln
    end
end
```

Figure A.1: Matlab Code: Reading the .vxp file's header

```
for i = 11:length(datm(3,:))-9
    if(all(datm(3,i-10:i-1) > 0) && all(datm(3,i:i+9) < 0) && ...
       all(ddatm(3,i:i+5) < 0))
        max_point(cnt_max) = i;
        cnt_max = cnt_max+1;
    end
    if(all(datm(3,i-10:i-1) < 0) && all(datm(3,i:i+9) > 0) && ...
       all(ddatm(3,i:i+5) > 0))
        min_point(cnt_min) = i;
        cnt_min = cnt_min+1;
    end
end
```

Figure A.2: Matlab Code: Finding peaks in the respiration curve

```
delete_max = [];
for i = 1:length(max_point)-1
    wrong_min = find(min_point > max_point(i) & min_point < max_point(i+1));
    if(isempty(wrong_min))
        % Kein Minumum zwischen den zwei Maxima
        if(atm(3,max_point(i)) > atm(3,max_point(i+1)))
            kleineres_max = max_point(i+1);
        else
            kleineres_max = max_point(i);
        end
        % Hier bezieht sich der Index nur auf den ausgewählten Bereich, es
        % muss also noch der Startindex dazugerechnet werden und -1!
        [moegliches_min, moegliches_min_index] = min(atm(3,max_point(i):max_point(i+1))
        moegliches_min_index = moegliches_min_index + max_point(i) - 1;
        if(moegliches_min < atm(3,kleineres_max)/2 && moegliches_max < 0.3)
            min_point = [min_point moegliches_min_index];
            min_point = sort(min_point);
        else
            delete_max = [delete_max i];
            max_point(i+1) = ceil((max_point(i) + max_point(i+1))/2);
        end
    end
end
max_point(delete_max) = [];
```

Figure A.3: Matlab Code: Finding overseen peaks in the respiration curve

```
delete_min = [];
delete_max = [];
for i = 1:length(max_point)
    if i <= length(min_point)
        if(abs(atm(2,min_point(i)) - atm(2,max_point(i))) < min_time_diff || ...
           abs(atm(3,min_point(i)) - atm(3,max_point(i))) < min_ampl_diff)
            delete_min = [delete_min i];
            delete_max = [delete_max i];
        end
    end
end
min_point(delete_min) = [];
max_point(delete_max) = [];
```

Figure A.4: Matlab Code: Deleting very close minima/maxima

```
ampl = (1+cos(2*pi*phase))/2;

if(phase >= 0.5)
    for i = 1:length(min_point)
        j = min_point(i);
        while (atm(3,j) < ampl && j < max_point(i+1))
           j = j + 1;
        end
        phase_index(i) = j;
    end
    for i = 1:length(phase_index)
           atm(3,phase_index(i)) = ampl;
    end
    trg = zeros(1,length(max_point));
    trg(1) = atm(2,max_point(1));
    for i = 1:length(phase_index)
        ampl_next_phase = atm(3,phase_index(i));
        time_next_phase = atm(2,phase_index(i));
        cph = 1-(acos(2*ampl_next_phase-1)/(2*pi));     %ph(2,:) = amplitude von atmung
        trg_a = (time_next_phase - trg(i))*(1-cph)/cph; %ph(1,:) = timestamp
        trg(i+1) = time_next_phase + trg_a;
        if (i <= (length(phase_index)-1) && trg(i+1) > (atm(2,phase_index(i+1))-1.0))
           trg(i+1) = atm(2,phase_index(i+1)) - 1.0;
        end
    end

else    % Phase < 0.5
```

Figure A.5: Matlab Code: Calculating triggers

Appendix B

Testing Results

Period	2000ms
Phase	Volume [cm^3]
0%	5,83507
10%	5,98311
20%	5,55773
30%	3,87963
40%	2,59488
50%	2,13551
60%	2,87457
70%	4,10619
80%	4,54329
90%	5,30265
Average	4,28126
SD	1,40122

(a) 2000ms

Period	2400ms
Phase	Volume [cm^3]
0%	0
10%	0,20195
20%	1,11717
30%	2,52379
40%	4,64915
50%	1,68982
60%	3,23003
70%	2,02028
80%	0,70663
90%	0
Average	1,613882
SD	1,53102

(b) 2400ms

Period	2800ms
Phase	Volume [cm^3]
0%	5,75460
10%	5,95108
20%	4,31048
30%	1,27576
40%	1,32225
50%	1,81794
60%	2,61363
70%	2,72105
80%	2,86480
90%	3,59799
Average	3,22296
SD	1,67680

(c) 2800ms

Period	3200ms
Phase	Volume [cm^3]
0%	1,40428
10%	0,07578
20%	0,00039
30%	0,48046
40%	2,13083
50%	3,16519
60%	7,25927
70%	8,10183
80%	4,07572
90%	2,83941
Average	2,95332
SD	2,83935

(d) 3200ms

Table B.1: Volumina per phase for test 4 - Part 1

Period	3400ms
Phase	Volume [cm^3]
0%	2,92730
10%	2,59410
20%	0,67187
30%	0
40%	1,20311
50%	2,59879
60%	4,21126
70%	7,25184
80%	5,07102
90%	3,20815
Average	2,97374
SD	2,15641

(e) 3400ms

Period	3600ms
Phase	Volume [cm^3]
0%	0,32539
10%	1,70661
20%	2,87535
30%	3,18120
40%	3,62612
50%	5,07531
60%	5,18547
70%	3,26362
80%	2,98042
90%	2,61480
Average	3,08343
SD	1,43367

(f) 3600ms

Period	3800ms
Phase	Volume [cm^3]
0%	2,60895
10%	3,01519
20%	3,25229
30%	3,39487
40%	3,37182
50%	3,95385
60%	3,26597
70%	2,88785
80%	1,74372
90%	2,30231
Average	2,97968
SD	0,62937

(g) 3800ms

Period	4000ms
Phase	Volume [cm^3]
0%	2,68238
10%	2,75386
20%	2,83238
30%	2,85855
40%	2,98081
50%	2,78277
60%	2,55465
70%	2,59605
80%	2,94761
90%	3,12964
Average	2,81187
SD	0,17772

(h) 4000ms

Table B.1: Volumina per phase for test 4 - Part 2

Period	4200ms
Phase	Volume [cm^3]
0%	3,00152
10%	3,04370
20%	3,05269
30%	1,44529
40%	2,85930
50%	1,81364
60%	2,73785
70%	3,15620
80%	3,01949
90%	4,09056
Average	2,82202
SD	0,73145

(i) 4200ms

Period	4400ms
Phase	Volume [cm^3]
0%	2,86246
10%	0,57851
20%	2,73629
30%	2,27575
40%	1,95739
50%	3,88471
60%	5,13391
70%	4,38509
80%	3,55620
90%	2,77652
Average	3,01468
SD	1,29853

(j) 4400ms

Period	4600ms
Phase	Volume [cm^3]
0%	2,55816
10%	0,08750
20%	2,64293
30%	2,09723
40%	0,80116
50%	3,16831
60%	5,09406
70%	6,02999
80%	3,28745
90%	3,23628
Average	2,90031
SD	1,76662

(k) 4600ms

Period	4800ms
Phase	Volume [cm^3]
0%	0
10%	2,52262
20%	2,63785
30%	1,06405
40%	4,70618
50%	8,51979
60%	5,63234
70%	1,67615
80%	2,93316
90%	2,52223
Average	3,22144
SD	2,47005

(l) 4800ms

Table B.1: Volumina per phase for test 4 - Part 3

Period	5200ms
Phase	Volume [cm^3]
0%	0,18750
10%	2,89761
20%	1,92302
30%	3,82494
40%	8,12527
50%	6,42256
60%	3,29253
70%	2,37614
80%	2,66598
90%	0
Average	3,17155
SD	2,51739

(m) 5200ms

Period	5600ms
Phase	Volume [cm^3]
0%	0
10%	2,63355
20%	4,52806
30%	4,73352
40%	4,90110
50%	4,95071
60%	3,97494
70%	3,39643
80%	1,42928
90%	0
Average	3,05476
SD	1,95615

(n) 5600ms

Period	6000ms
Phase	Volume [cm^3]
0%	0,45156
10%	2,99878
20%	3,19136
30%	2,09958
40%	2,73004
50%	5,72179
60%	6,11944
70%	5,44836
80%	0
90%	0,57577
Average	2,93367
SD	2,24552

(o) 6000ms

Table B.1: Volumina per phase for test 4 - Part 4

Constant	period
Phase	Volume [cm^3]
0%	3,19370
10%	3,29058
20%	3,38471
30%	3,02574
40%	3,11792
50%	2,86871
60%	3,33706
70%	4,49329
80%	4,29681
90%	3,41518
Average	3,44237
SD	0,53150

(a) Constant period

Standard	procedure
Phase	Volume [cm^3]
0%	3,12339
10%	3,17300
20%	3,33784
30%	3,02652
40%	3,04956
50%	2,86988
60%	3,33745
70%	4,48079
80%	4,25501
90%	3,34722
Average	3,40007
SD	0,53552

(b) Standard procedure

New method	same for all phases
Phase	Volume [cm^3]
0%	3,10152
10%	3,11128
20%	3,31597
30%	2,95738
40%	2,94449
50%	2,78668
60%	3,19253
70%	4,38275
80%	4,27611
90%	3,33823
Average	3,34069
SD	0,54814

(c) New method: Same breathing signal for all phases

New method	individually per phase
Phase	Volume [cm^3]
0%	3,10777
10%	3,13003
20%	3,26987
30%	3,01675
40%	2,98042
50%	2,79722
60%	3,25190
70%	4,32142
80%	4,26361
90%	3,30737
Average	3,34464
SD	0,52241

(d) New method: Individual breathing signal per phase

Table B.2: Comparison: Volumes per phase of test 3

Standard	procedure
Phase	Volume [cm^3]
0%	4,01299
10%	3,48798
20%	4,06729
30%	4,11495
40%	3,25321
50%	2,67077
60%	3,00125
70%	3,51454
80%	3,91572
90%	4,15987
Average	3,619857
SD	0,51912

(a) Standard procedure

New method	individually
Phase	Volume [cm^3]
0%	3,66650
10%	3,45399
20%	3,99737
30%	3,90478
40%	3,20203
50%	2,52194
60%	2,91765
70%	3,60478
80%	3,92314
90%	4,09463
Average	3,52868
SD	0,51218

(b) New method: Individual breathing signal per phase

Period	2 seconds
Phase	Volume [cm^3]
0%	3,82939
10%	3,39696
20%	3,91494
30%	3,96377
40%	3,15242
50%	2,36256
60%	2,91453
70%	3,46415
80%	3,90713
90%	3,87392
Average	3,47780
SD	0,53393

(c) Trigger every 2 seconds

Table B.3: Comparison: Volumes per phase of test 4

Standard	procedure
Phase	Volume [cm^3]
0%	8,10808
10%	7,64168
20%	6,79365
30%	5,31126
40%	3,50698
50%	3,46792
60%	3,92807
70%	4,02416
80%	4,21751
90%	6,35225
Average	5,33516
SD	1,76219

(a) Standard procedure

by software	2 seconds
Phase	Volume [cm^3]
0%	8,14363
10%	7,88660
20%	4,33197
30%	5,44992
40%	3,52338
50%	3,37925
60%	3,95150
70%	4,07455
80%	4,21283
90%	6,39600
Average	5,13496
SD	1,76424

(b) Triggers every 2 seconds by software

Trigger-Box	2 seconds
Phase	Volume [cm^3]
0%	5,55124
10%	4,51946
20%	5,04641
30%	6,63545
40%	6,10577
50%	7,99832
60%	6,04522
70%	5,70929
80%	6,90068
90%	6,71826
Average	6,12301
SD	0,99852

(c) Triggers every 2 seconds by hardware

Trigger-Box shifted	2 seconds
Phase	Volume [cm^3]
0%	5,63195
10%	4,55774
20%	5,29758
30%	6,66592
40%	8,87799
50%	7,99285
60%	6,09483
70%	5,95499
80%	6,87685
90%	6,86826
Average	6,48190
SD	1,27446

(d) Triggers every 2 seconds by hardware and shifted

Table B.4: Comparison: Volumes per phase of test 5

Box 2500ms	Rec. 2500ms
Phase	Volume [cm^3]
0%	2,59098
10%	3,22495
20%	5,12531
30%	6,77646
40%	5,48234
50%	3,46995
60%	3,37768
70%	3,69369
80%	4,19369
90%	3,10855
Average	4,12236
SD	1,29291

(a) Box 2500ms - Rec. 2500

Box 2500ms	Rec. 5000ms
Phase	Volume [cm^3]
0%	2,50934
10%	3,25073
20%	4,98860
30%	6,83701
40%	5,57023
50%	3,62651
60%	3,45620
70%	3,70580
80%	4,25033
90%	3,25698
Average	4,14517
SD	1,29961

(b) Box 2500ms - Rec. 5000

Box 5000ms	Rec. 2500ms
Phase	Volume [cm^3]
0%	4,90969
10%	6,81787
20%	7,20106
30%	5,38156
40%	4,77649
50%	3,95814
60%	4,19603
70%	3,52963
80%	4,01260
90%	4,33509
Average	4,91782
SD	1,22390

(c) Box 5000ms - Rec. 2500

Box 5000ms	Rec. 5000ms
Phase	Volume [cm^3]
0%	5,13117
10%	6,53740
20%	7,01982
30%	5,40812
40%	4,72884
50%	3,88314
60%	4,03900
70%	3,33589
80%	3,89564
90%	4,33704
Average	4,83161
SD	1,20260

(d) Box 5000ms - Rec. 5000

Table B.5: Volumes per phase for test 6

shift	all but first
Phase	Volume [cm^3]
0%	4,22823
10%	5,87124
20%	7,08885
30%	5,64936
40%	4,90442
50%	3,82744
60%	3,92080
70%	3,90869
80%	3,54540
90%	4,09815
Average	4,70426
SD	1,15151

(a) Shifting all triggers but first

shift	all
Phase	Volume [cm^3]
0%	4,13174
10%	5,93765
20%	7,04822
30%	5,63686
40%	4,79371
50%	3,83213
60%	3,99502
70%	3,86728
80%	3,49774
90%	4,00166
Average	4,67420
SD	1,16072

(b) Shifting all triggers

randomly	distributed
Phase	Volume [cm^3]
0%	4,16456
10%	5,90440
20%	6,86697
30%	5,67163
40%	4,79582
50%	3,86963
60%	3,88135
70%	3,80283
80%	3,52860
90%	4,02705
Average	4,65128
SD	1,12310

(c) Randomly distributed triggers

first and last	only
Phase	Volume [cm^3]
0%	4,19620
10%	5,94273
20%	7,09119
30%	5,75561
40%	4,84075
50%	3,89385
60%	3,90596
70%	3,89307
80%	3,60829
90%	4,14229
Average	4,72699
SD	1,15841

(d) Only first and last trigger

Table B.6: Volumina per phase for test 7 - Part 1

deleted	all triggers
Phase	Volume [cm^3]
0%	4,12628
10%	5,87202
20%	6,88416
30%	5,43256
40%	4,73801
50%	3,81728
60%	3,84306
70%	3,81260
80%	3,49540
90%	3,98174
Average	4,60031
SD	1,11455

(e) Deleted all triggers

Table B.6: Volumina per phase for test 7 - Part 2

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