Breathing Movement Analysis for Adjustment of Radiotherapy Planning

M. Penhaker, M. Novakova, J. Knybel, J. Kubicek, J. Grepl, V. Kasik and T. Zapletal

Abstract Aim of this work is the developing of algorithm, which extract and process the breathing movement data from CyberKnife log files for prospective conventional radiotherapy planning. The described algorithm enable verification and accuracy of the settings radiated tumor rims, which are used in conventional radiotherapy. This results should contribute to improving of the treatment of irradiated tumors with possible subsequent statistical evaluation.

Keywords Radiotherapy · Breath movement · CyberKnife · Unfavorable movements · Dose accuracy · Therapy

1 Introduction

Currently much research medicine focused on the most efficient treatment of tumors. In connection with it was put into operation CyberKnife radiotherapy machine, which now rank among the best that the irradiation of tumor tissue was

M. Penhaker (✉) · M. Novakova · J. Knybel · J. Kubicek · J. Grepl · V. Kasik
VSB – Technical University of Ostrava, FEECS, K450, Ostrava, Czech Republic
e-mail: marek.penhaker@vsb.cz

M. Novakova
e-mail: marketa.novakova@vsb.cz

J. Knybel
e-mail: Jakub.knybel@fno.cz

J. Kubicek
e-mail: jan.kubicek@vsb.cz

V. Kasik
e-mail: vladimir.kasik@vsb.cz

J. Knybel · T. Zapletal
Faculty Hospital, Ostrava, Czech Republic
e-mail: tomas.zaletal@fno.cz

D. Król et al. (eds.), *Advanced Topics in Intelligent Information and Database Systems*, Studies in Computational Intelligence 710,
DOI 10.1007/978-3-319-56660-3_10

developed. Among the most accurate technique to a tenth of a centimeter. However, even though errors occur and unnecessary contact with healthy tissue. And therefore constantly looking for new techniques that would be able to prevent such damage. CyberKnife instrument can also contribute in many ways when compared with the treatment that has been used as conventional radiotherapy and may show us whether the set parameters are sufficient, even when moving bearings caused breathing and other adverse effects. These movements are physiological components of the organism, which cannot be suppressed or eliminated [1, 2].

For by monitoring the patient's respiration waveform which arises due CyberKnife device during irradiation of a patient, detect deviations from tidal breathing patient to avoid unnecessary exposure of healthy tissue and this therapy was thus much more precise. CyberKnife device can compensate for an unwanted movements at millimeter level. In conventional radiotherapy so but not to the tumor and is attributed to the large safety rim. It was compared with data resulting from this program should be able to compare whether they are currently set up hems with conventional radiotherapy correct, or the percentage of cases that do not respond due to physiological movements of the patient's body [3, 4].

1.1 Reference Data

Before starting treatment, it is necessary to obtain reference data. Before shooting this data is acquired several radiographs. These images are scanned at an angle of 45° left and right of the patient's X-ray tubes, which are part of the device CyberKnife and are located near the ceiling of the facility. It is necessary to obtain a correlation model, which is determined by X-ray images in different phases of the respiratory movements, the system then has available information, wherein the bearing is in which phase of respiration. With this correlation model, the patient can be monitored during therapy because of armor, who wears three LEDs. They are captured by a special camera. After X-rays are taken at certain intervals to check whether the bearing position corresponds to the original model. Thus is obtained the breathing curve of the patient [5–7].

2 Problem Definition

Patient motion during radiation are stored in the. Log. This file is being prepared in the course of treatment, when the patient is wearing a special vest with LEDs. The movements of these diodes are scanned by special camera and motion information is written as an indication of patient movement in all 3 directions of movement in time.

Log always starts with a blank line, followed by information about the time when treatment was initiated. This time is given in seconds since midnight. On the third line there is information about the patients themselves. The data are in four columns. The first column is about time, therefore the length of irradiation. The remaining three columns of information about the movement of deposits during treatment. Is in the 3D system, it is therefore the X, Y, Z, the corresponding motions in direction X = Superior-Inferior (from head to feet), Y = leftright or laterolateral (left and right) and Z = anteriorposterir (from back to belly). Coordinates in one log may vary abruptly, because of treatment interruption and repositioning of the patient. The frequency of the resulting record is 25 Hz, i.e. 25 frames per second. The recording time is determined by the length of the actual treatment and the number of records for each patient is determined by the number fraction.

It is necessary to keep patient information. The log regards social security number and name. The main result should be the maximum and minimum values of deflections movement irradiated and monitored bearings. It is necessary to filter out the curve overshoot and adjust for desired outcomes. These data statistically to express their incidence and prevalence. Determine when treatment was discontinued. This can be detected thanks to longer delays in the first column of the log. It is necessary to keep the information about the number of interruptions during treatment to determine total treatment time, including delays in discontinuation without it. Visually is then displayed motion bearings in space [8–10].

When using the conventional method is a safety rim is set in the order of several centimeters, as opposed to device CyberKnife this rim can be minimized to a few millimeters. The rim is important to cover the vicinity of the tumor, which can be moved by moving the patient. In conventional radiotherapy is the rim more, because it is not possible to monitor and correct the patient's movement and must therefore cover the entire irradiated tumor size at all stages of the respiratory cycle. Use of the proposed program will help process the data from the respiratory curves, which are obtained during treatment. It should be developed, to improve current treatment of irradiated tumors.

The algorithm proposed for processing respiratory waveform will be used for control. Combining monitoring of respiratory curve in patients treated at the unit CyberKnife and conventional radiotherapy can be proved whether the security hem with conventional therapy.

Data processed and visualized in the program can and will be used for subsequent irradiation postanalysis quality and design of optimal methods of radiation and radiological treatment approaches.

3 Breath Movement Signal Analysis

The main objective of this work is to develop algorithm that would be able to modify data and display the requested information, including information on the treatment, the patient information. The program should be able to proceed the data from the respiratory curve overshoot using a suitable filter, display amplitude of respiration curve and calculate statistics on discontinuation of therapy, duration of each segment, and the number of deep breaths, which is necessary to set an appropriate function. Very important fact is also the sum of all departments, which indicates the duration of the treatment. Other requirements include displaying only the amplitude of the curve, i.e. their extremes, which correspond to the maximum inspiratory and expiratory time low. The final requirement for the output of the software is the ability to export the modified values in the file that would be possible to continue to process mathematical software.

In the case of the creation of this algorithm, you can use it for planning radiotherapy alone for patients and a treatment could then become again a little more accurate. Serve for processing already ex post treatment and statistical processing of patient motion and physiological movements in his body during treatment, which affect the actual course of irradiation. Will be used to control when the conventional radiation therapy that has been proven whether the currently set values of safety rim sufficient. All data will be possible to continue to process and gain better insights [11–18].

3.1 Source Data

Log file type is produced CyberKnife device. It contains information about a patient's course of treatment. Data on patient movement is written in three-dimensional system for the duration of radiation in real time under the name of the file. In the event log file type, it is necessary to make adjustments to allow data from it to correctly handle and apply. Log file type can be seen in the following figure (Fig. 1).

The first line in the file is empty. The second line indicate the date and time of patient treatment. The third line includes patient data. Patient's surname and birth number is hidden intentionally in order to preserve the anonymity of the patient's personal data. On the fifth row start to read data during treatment.

When you view the x-axis without modification can see a large number of confusing data, straight sections, which means interruptions. It is therefore easily detectable eye of times the treatment was discontinued. These sections are not alone when viewing axis desirable. Curve is necessary to exterminate them, but to

```
48708.659 DATE_ANCHOR Wed 03 Oct 2012 13:31:48
48708.659 INFO --> LoggerHandler::init: initialized id 6 with file [illegible]_[illegible]_03Oct12_133148/Modeler.
48708.659 INFO --> Modeler log started Wed Oct 03 13:31:48 Central Europe Daylight Time 2012
        30149.248:-4.227 12.332 0.958
        30149.287:-4.213 12.339 0.925
        30149.325:-4.140 12.378 0.747
        30149.363:-4.057 12.422 0.547
        30149.401:-4.029 12.437 0.480
        30149.440:-4.043 12.430 0.514
        30149.478:-4.043 12.430 0.514
        30149.517:-3.997 12.454 0.403
        30149.556:-3.946 12.481 0.280
        30149.594:-3.923 12.494 0.225
```

Fig. 1 The original log file type of device CyberKnife preserve the value of extremes. It may be noted periods corresponding sleep stages of treatment, when the patient is almost at rest and respiratory amplitude are almost identical, these findings can be seen mainly in the second half of the treatment.

3.2 Conversion of Angle

Data are recorded during treatment relative to the robot, which performs irradiation. For this reason, data spin about −45° relative to the patient. It is therefore necessary before rendering and other processing data converted by +45° (Fig. 2).

$$
\begin{aligned}
x_{(45^\circ)} &= (x^* \cos 45^\circ) - (y^* \sin 45) = (x^*0.7071) - (y^*0.7071) \\
y_{(45^\circ)} &= (y^* \cos 45^\circ) - (y^* \sin 45) = (x^*0.7071) - (y^*0.7071)
\end{aligned} \tag{1}
$$

Each line of the log header including the time stamp. Time is measured in seconds since midnight, so it is necessary to convert these confusing numbers so they can be displayed as a time. The time is needed to view such information in the data table program, which displays the time of the header file that is stored in the data structure and is not recalculated, since there is no time to be recalculated.

During the treatment can occur to interruptions process, which are recorded as a crack in time sequence. These interruptions are most often due to readjustment of the patient has occurred, for example, motion to move the robot and the patient needs to get back into position to deposit illuminating correctly.

To determine the number of interruptions is running string, which explores times in the first column of the array and compared one after another. When it detects the difference in time greater than 0.1 s are entered information that the interruption has occurred. Indication of interval data to which it belongs, is listed in the blank

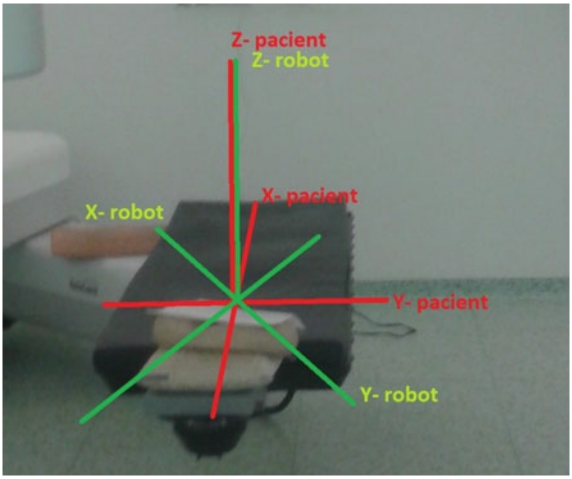

Fig. 2 Description axes to the robot and to the patient

columns per row, it is subsequently traceable in the process the data is located, and also the number of times and the treatment was interrupted for whatever reasons. A line number at which interruption occurred while the recorded lap time, i.e. the length of time before the interruption.

3.3 Filtering Data

Data is written to the log of the frequency of 25 Hz. Companies such data in such a small time deviation cause considerable noise. For better display of curves it is essential to filter out data from all that is required. However, it is necessary to hold all the highs and lows of their value. The following figure shows the loaded breathing curve of the original data before filtering. They are clear overlaps and noise that would be for the following functions for finding maxima were considerable difficulties, and therefore it is necessary to eliminate these shortcomings (Fig. 3).

Processing of these signals was elected FIR filter. The values specified for the value of m is created ideal low-pass filter, which in the lower frequency signal outlet and upper frequencies suppresses signal. Filter Design (FIR 2 (30 f, m)) with the length of the pulse characteristics 30, was selected parameter as a compromise. The higher the value, the better the filter filters, but it is even more difficult to calculate. The filter is configured by the constants f and m. Then, the run command "filtfilt", the filtering without signal delay. This prevents unnecessary calculations and the process will accelerate. After starting the filter, they retained value extremes and timeline. To remove all unnecessary fluctuations in the signal (Fig. 4).

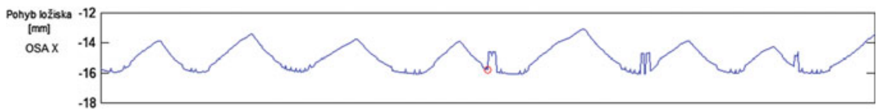

Fig. 3 Raw data from the log file containing information about the movement of breathing of the patient during treatment

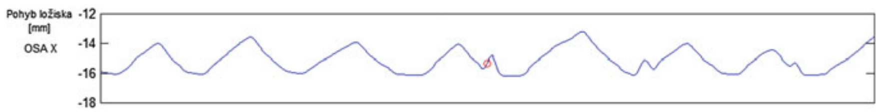

Fig. 4 Using FIR2 filter settings f = [0, 0.15, 0.15, 1] on the log file containing information about the movement of breathing of the patient during treatment

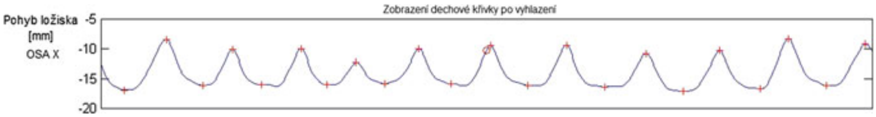

Fig. 5 Finding and marking extremes on breathing curve

3.4 Extremes

Extremes in a dataset representing the function of inhalation and exhalation, thus peaks curve. Their read correctly is important for some other functions, such as the number of deep breaths, deep breaths number, complete the maximum or minimum in the sector.

Extremes are sought through mathematical functions with the second derivative. This function compares point by point on each axis and searches extremes, if the scanned value is not extreme, is entered into the line as zero, otherwise, if the extremum thus found, its value is entered. In this case, therefore extrema written to one line and therefore cannot recognize if it is a maximum or minimum respectively extremes are not divided at the maximum and minimum. The program extremes shown as red crosses axes (Fig. 5).

Due to the large amount of data frequently a situation that is as extreme deemed value that only slightly advanced, but not the apex inhale or exhale, so the program functions (MaxMin), which compares consecutive searched extremes and seeks all that differ from each other by a value of 30. It is thus ensured that successive extrema better match the actual breathes. It is also high probability that of the peak will be followed by a minimum and maximum after him. The coefficient 30 is set so that the error is minimized depending on the files to be tested.

The following figure sought extremes without MaxMin used functions, i.e. without setting the minimum difference between two adjacent extremes. It is obvious that this function does not work correctly as it will help us find consecutive inhale and exhale.

In the data extremes are found in a small percentage of data inaccuracies that arise signal filtering and search entry highs and lows. The configuration is such that the errors are minimized. Errors were counted during final testing.

The resulting error is less than 5% and for the use of this program is the magnitude of this error is acceptable.

4 Representation of Algorithm Outputs

To visualize the proposed algorithm was used environment in MATLAB GUI editor. Beneath frames and tables are displayed itself breathing curves for each axis separately. The x-axis is additionally appear dimmed and ghosted interruption, at

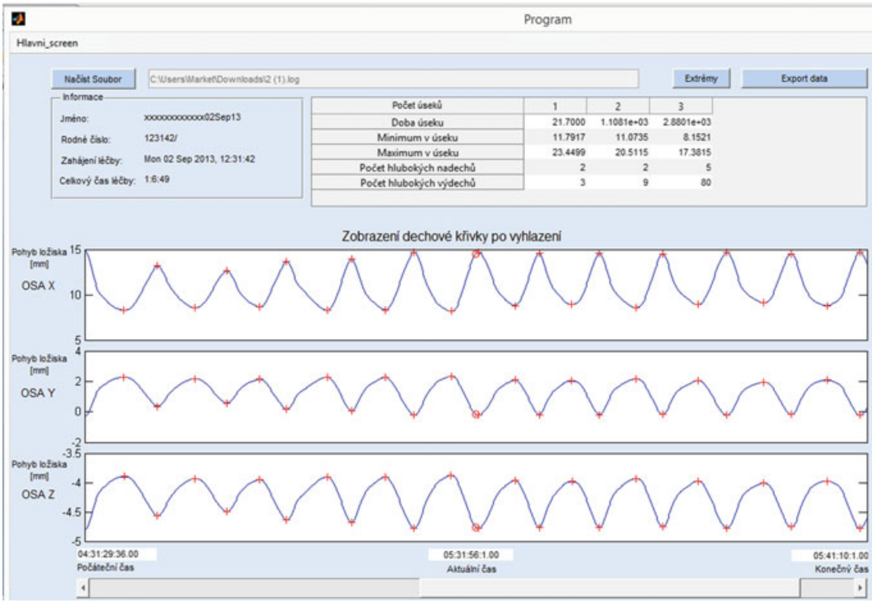

Fig. 6 User interface for visualization of algorithms for processing breathing curves from data log files CyberKnife system

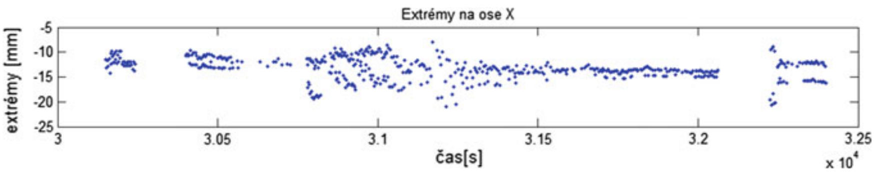

Fig. 7 Trend visualization of extreme breaths on the processed data

the point where you stopped the treatment and readjustment of the position of the patient. Red dots on the axes are extremes. Ranges on the axes of each graph are automatically adjusted by the program needs to be arranged graphs (Fig. 6).

Extremes are displayed in all three axes and the main program for each curve as red crosses. Only extremes for each axis without the original curve, the dot plot. Thus viewed extremes are much clearer than if they were shown the original curve (Fig. 7).

5 Testing of the Algorithm

An important part of the testing was to determine how big bug occurs when displaying highs and lows limits. Due to the large amount of data when the number of extremes in the order of several hundred to several thousand, it was not possible to go through the entire curve, that was calculated, how many errors occurs in each file. Were selected because 300 values in each file. The first 100 values at the beginning of treatment, the second 100 values from the center of treatment and the last 100 values from the end of treatment. Number of errors on all 300 values were averaged and converted to an error in percentage terms. This error in neither case did not exceed 5%. All values are only approaching this value. Given the large number of data this error is acceptable to use the program.

Another important point was to test whether the data is loaded and displayed. This has been proven by in the left frame to monitor the patient and displays graphs breathing curves in all three axes. Because the display feature followed immediately successive additional functions, it is therefore necessary to work load at 100% files. All remaining functions in the file is loaded as those that calculate and display the number of sections, the number of deep breaths, time segments, total treatment time, and other extremes.

During testing on all available files file was not found, for which the program had a single mistake. Not found error that would prevent proper operation of the program. Set functions thus meet the requirements of the assignment. The following table demonstrates the functionality at the ten test files. I bearing have been known in the file name. Necessary information has been reading the data, the total time of patient treatment, the number of found extremes, number of sections, a number of treatment interruption, whether the program is able to export data, whether it worked button display the extremes of the controlled values, errors in these controlled areas and conversion to error in percentage. On average, the bug was found in the extremes of 2.75%. It is a value calculated from the following table.

The table shows in the first column of the registered name bearing. This figure is nowhere mentioned in the log, I was known from the filename of the program for testing and demonstrating the functionality of the program for different areas of bearing position. The second column refers to retrieve the file (Table 1).

If the file is loaded the table is yes or no, if not to load the file. Total time is displayed in the program after the file is loaded, its values are given in the table as the next column. Its distinct values show that there were different types of files. The number of sections is again what is shown in the program. Demonstrates the functionality of sub-functions program, which seeks discontinuation. Presented value once again demonstrates the functionality of the program. The following column has an export value of yes/no to the functioning/malfunctioning button to export the data and create a .xlsx file. The fact that the file is created correctly, demonstrates additional column that shows the number of extremes. This value is only deductible in the program from an open file .xlsx, a complement to the table proves correct functionality. Column to view the extremes again has a value of

Table 1 Testing results processing algorithm breathing curve of log files

Bearings	Loading	Total time of therapy	Number of segments	Export	Number of extremes	Visualization of extremes	Verified extremes	Errors in extremes	Error in %
Hepar	Yes	1:53:18	3	Yes	2515	Yes	300	6	2
Hepar	Yes	1:39:45	4	Yes	3316	Yes	300	5	1.6
Hepar	Yes	0:58:37	2	Yes	881	Yes	300	3	1
Lungo	Yes	0:31:45	4	Yes	534	Yes	300	12	4
Lungo	Yes	0:59:39	5	Yes	1516	Yes	300	13	4.3
Lungo	Yes	0:55:40	6	Yes	1330	Yes	300	10	3.3
Lungo	Yes	1:02:27	1	Yes	1545	Yes	300	15	5
Lungo	Yes	0:34:31	1	Yes	903	Yes	300	3	1
Pankreas	Yes	1:13:05	7	Yes	1330	Yes	300	9	3
Pankreas	Yes	1:08:25	2	Yes	1843	Yes	300	7	2.3

yes/no buttons for functionality extremes. If you have been pane extremes in the column value is yes, otherwise not. The last three columns refer to testing extremes and their errors in the program. The first of these three columns is the number of extremes that have been evaluated. The second column is the number of errors found in these extremes. Whether it was the extreme, the program skipped or wrongly diagnosed. Number of false extremes falls on previous data tables. The last column is then calculation error in %.

6 Conclusion

In this work, we were created by an algorithm that has been designed for the analysis of breathing curve motion bearings with correction therapeutic dose. When testing the algorithm, it was found that the error of irradiation ranging up to 5%, which is due to the large number of motion data can be accepted. Of analyzed the respiratory movements can also determine how many times the treatment was interrupted, and how long it took each section as many times as there was a deep inhale or exhale, and how long it lasted the entire treatment cycle without interruption.

Acknowledgements The work and the contributions were supported by the project SV4506631/2101 'Biomedical Engineering Systems XII'. This work was supported by The Ministry of Education, Youth and Sports from the National Programme of Sustainability (NPU II) project "IT4Innovations excellence in science - LQ1602". This article has been supported by financial support of TA ČR, PRE SEED Fund of VSB-Technical university of Ostrava/TG01010137.

References

1. Yamada, S.M., Ishii, Y., Yamada, S., Kuribayashi, S., Kumita, S., Matsuno, A.: Advanced therapeutic strategy for radiation-induced osteosarcoma in the skull base: a case report and review. Radiat. Oncol. **7** (2012)
2. Xie, Y., Xing, L.: Intrafractional motion of the pancreas during cyber knife radiation therapy. Int. J. Radiat. Oncol. Biol. Phys. **81**, S789–S789 (2011)
3. Kim, J.B., Hwang, Y., Bang, W.C., Kim, J.D.K., Kim, C.: IEEE: real-time moving organ tracking in ultrasound video based on a 3D organ model (2012)
4. Sherwood, J.T., Brock, M.V.: Lung cancer: new surgical approaches. Respirology **12**, 326–332 (2007)
5. Bogart, J.A.: Stereotactic body radiotherapy for poor-risk lung cancer: "More cyber, less knife?". Cancer J. **13**, 75–77 (2007)
6. Karaman, K., Dokdok, A.M., Karadeniz, O., Ceylan, C., Engin, K.: Intravascular placement of metallic coils as lung tumor markers for cyberknife stereotactic radiation therapy. Korean J. Radiol. **16**, 626–631 (2015)

7. Rashid, A., Mone, P., Sarfaraz, M.: Predicting late lung complications following lung tumor radiosurgery with cyber knife using biologically effective doses and normalized dose-surface histograms. Med. Phys. **34**, 2482 (2007)
8. Tezcanli, E.K., Goksel, E.O., Yildiz, E., Garipagaoglu, M., Senkesen, O., Kucucuk, H., Sengoz, K.M., Aslay, I.: Does radiotherapy planning without breath control compensate intra-fraction heart and its compartments' movement? Breast Cancer Res. Treat. **126**, 85–92 (2011)
9. Wang, J., Zhong, R.M., Bai, S., Lu, Y., Xu, Q.F., Zhou, X.J., Xu, F.: Evaluation of positioning accuracy of four different immobilizations using cone-beam ct in radiotherapy of non-small-cell lung cancer. Int. J. Radiat. Oncol. Biol. Phys. **77**, 1274–1281 (2010)
10. Wong, V.Y.W., Tung, S.Y., Ng, A.W.Y., Li, F.A.S., Leung, J.O.Y.: Real-time monitoring and control on deep inspiration breath-hold for lung cancer radiotherapy-combination of ABC and external marker tracking. Med. Phys. **37**, 4673–4683 (2010)
11. Bettinardi, V., Picchio, M., Di Muzio, N., Gianolli, L., Messa, C., Gilardi, M.C.: PET/CT for radiotherapy: image acquisition and data processing. Q. J. Nucl. Med. Mol. Imaging **54**, 455–475 (2010)
12. Brock, J., McNair, H.A., Panakis, N., Symonds-Tayler, R., Evans, P.M., Brada, M.: The use of the active breathing coordinator throughout radical non small-cell lung cancer (NSCLC) radiotherapy. Int. J. Radiat. Oncol. Biol. Phys. **81**, 369–375 (2011)
13. Cole, A.J., Hanna, G.G., Jain, S., O'Sullivan, J.M.: Motion management for radical radiotherapy in non-small cell lung cancer. Clin. Oncol. **26**, 67–80 (2014)
14. Hu, W.G., Ye, J.S., Wang, J.Z., Xu, Q., Zhang, Z.: Incorporating breath holding and image guidance in the adjuvant gastric cancer radiotherapy: a dosimetric study. Radiat. Oncol. **7** (2012)
15. Kovacs, A., Hadjiev, J., Lakosi, F., Antal, G., Vandulek, C., Ezer, E.S., Bogner, P., Horvath, A., Repa, I.: Dynamic MR based analysis of tumor movement in upper and mid lobe localized lung cancer. Pathol. Oncol. Res. **15**, 269–277 (2009)
16. Macrie, B.D., Donnelly, E.D., Hayes, J.P., Gopalakrishnan, M., Philip, R.T., Reczek, J., Prescott, A., Strauss, J.B.: A cost-effective technique for cardiac sparing with deep inspiration-breath hold (DIBH). Physica Medica-Eur. J. Med. Phys. **31**, 733–737 (2015)
17. Nemoto, K., Oguchi, M., Nakajima, M., Kozuka, T., Nose, T., Yamashita, T.: Cardiac-sparing radiotherapy for the left breast cancer with deep breath-holding. Jpn. J. Radiol. **27**, 259–263 (2009)
18. Roth, J., Maleika, A., Engenhart-Cabillic, R., Strassmann, G.: Radiotherapy of the breast under breathhold. Geburtshilfe Und Frauenheilkd **70**, 812–816 (2010)