Contouring the Middle and Inner Ear on Radiotherapy Planning Scans

Heather D. Pacholke, MD, Robert J. Amdur, MD, Ilona M. Schmalfuss, MD, Debbie Louis, CMD, and William M. Mendenhall, MD

Abstract: The purpose of this study was to establish guidelines that help radiation oncologists contour the inner and middle ear on treatment planning scans. The radiotherapy computed tomography (CT) scans of 15 previously treated patients were reviewed for the ability to identify 3 separate auditory structures. The middle ear, the cochlea, and the vestibular apparatus were identified and contoured on each scan using anatomic landmarks. The volume and maximum axial dimension of each contour were calculated. The middle ear, cochlea, and vestibular apparatus were identified on all scans. The middle ear was defined by the tympanic membrane laterally and by the interface between air and the temporal bone in all other directions. The plane of the internal auditory canal through the temporal bone was the landmark distinguishing the vestibular apparatus from the cochlea. The mean volume of the middle ear, vestibular apparatus, and cochlea were 0.58 cm^3, 0.44 cm^3, and 0.14 cm^3, respectively. The maximum axial dimension across the contour averaged 1.57 cm for the middle ear, 1.10 cm for the vestibular apparatus, and 0.69 cm for the cochlea. A reference atlas was constructed that shows the contour of each structure on 5 consecutive CT images. Accurate identification of the middle ear and inner ear structures on radiotherapy planning scans is possible and is necessary if critical auditory organs are to be spared during radiotherapy of targets that are located near the base of the skull. The information generated in this study will help radiation oncologists contour auditory structures accurately.

Key Words: radiotherapy, ear, treatment planning

(*Am J Clin Oncol* 2005;28: 143–147)

Decreased hearing and problems with balance are well-described complications of radiotherapy to the middle and inner ear.[1–3,7] To decrease the auditory and vestibular complications of radiation therapy to the temporal bone, multiple groups advocate the use of complex radiation delivery systems such as intensity modulated radiation therapy (IMRT) or proton beam therapy that are able to generate dose distributions with a steep dose gradient across the auditory apparatus.[1,4,10] Application of such complex radiation delivery systems requires that the contouring of structures be as accurate as possible. The small size of the inner ear and close proximity to the target volume is such that small errors in contour definition may have a major effect on the quality of the radiotherapy plan and the risk of posttreatment sequelae.

In our department, we frequently treat patients with tumors near the temporal bone where it is desirable to minimize the dose to the middle and inner ear (eg, medulloblastoma, meningioma, paraganglioma, and parotid tumors). As we began using more sophisticated radiation delivery systems, we realized that there is a lack of clear guidelines on how to identify the boundaries of the middle and inner ear structures on treatment planning scans. We reviewed the published articles and textbook chapters that contained information relating to this subject but did not find information in a format that met our needs. We consulted our neuroradiology colleagues and references that describe the radiographic anatomy of the auditory apparatus.[5,6] From this effort, we established guidelines for contouring the middle ear and the 2 major components of the inner ear (the vestibular apparatus and cochlea) that have improved the quality and efficiency of the radiotherapy planning process in our department. The purpose of this article is to explain these guidelines in a way that will be of practical value to other clinical radiation oncology departments.

MATERIALS AND METHODS

There are 4 main goals of this project:

1. To determine if it is possible to identify the middle ear, vestibular apparatus, and cochlea on radiotherapy treatment planning scans.
2. To identify anatomic landmarks that help radiation oncologists contour the middle ear, vestibular apparatus, and cochlea on radiotherapy treatment planning scans.

From the Department of Radiation Oncology, University of Florida, Gainesville, FL.

Reprints: Robert J. Amdur, MD, Department of Radiation Oncology, University of Florida, 2000 SW Archer Road, PO Box 100385, Gainesville, FL 32610. Email: amdurrj@shands.ufl.edu.

ISSN: 0277-3732/05/2802-0143

DOI: 10.1097/01.coc.0000143847.57027.16

3. To establish reference values for the volume and maximum axial dimension of the middle ear, vestibular apparatus, and cochlea on radiotherapy treatment planning scans.
4. To organize a series of images that will serve as a reference atlas for contouring auditory structures for radiotherapy planning.

To accomplish these goals, we reviewed 15 computed tomography (CT) scans that had been used to plan radiotherapy treatments in our department over the past few years. To determine if head position or age affected the results, we included 5 scans from adults with the head in a neutral position, 5 adults with the head in an extended position (as used to treat paranasal sinus tumors), and 5 children (median age, 10 years; range, 4–12 years) who were treated with craniospinal irradiation in the prone position. For this project, we chose the first 5 scans that we could retrieve from our database in each of the 3 study groups. All planning scans were performed on a Phillips PQ 6000 scanner with a field of view of 48 × 48 cm and a matrix of 512 × 512 pixels yielding a spatial resolution of 0.94 mm. The CT scans were performed as contiguous slices of 3 mm thickness in adults and of 5 mm thickness in children. The same radiation oncologist (H.P.) and neuroradiologist (I.S.) reviewed each of the planning scans to determine if the auditory structures and major anatomic landmarks could be accurately identified. On each scan, the goal was to contour 3 separate structures: the middle ear, the cochlea, and the vestibular apparatus. Both reviewers were in agreement on all conclusions and finalized contours.

We calculated the volume and maximum axial dimension of each contour using commercial treatment planning software (Pinnacle version 6.2b). Only the "Organ At Risk Volume" as defined by ICRU report 62 was recorded.[8] To determine the "Organ At Risk Volume," each of the structures of interest was traced along its outer border, including the semicircular canals. Therefore, the small portion of the temporal bone enclosed by a semicircular canal (eg, lateral semicircular canal) was included within the volume. The volume of the 3 semicircular canals and the vestibule was combined as the volume of the vestibular apparatus. To calculate the maximum axial dimension of each contour, we first identified the scan slice where the contour was the largest and then recorded the maximum distance across the contour.

RESULTS

Ability to Identify Auditory Structures on Radiotherapy Planning Scans

The middle ear, as an air-filled structure with a sharp interface to the surrounding bone, was visualized on at least 3 images on all treatment planning scans. We were able to identify the cochlea and vestibular apparatus on all 15 scans. The cochlea was visible on at least 3 images in all cases when the slice thickness was 3 mm (10 patients). The cochlea was visualized on only 2 images in 3 of the 5 pediatric cases in whom the slice thickness was 5 mm. In the remaining 2 cases, the cochlea was seen on 3 images. The vestibular apparatus was visualized on at least 3 images in all 15 cases.

Identification of Landmarks for Contouring the Middle Ear, Vestibular Apparatus, and Cochlea

Middle Ear

Bony prominences mark the location of the tympanic membrane (Fig. 1). The anterior, posterior, and medial boundaries of the middle ear cavity are defined by the interface between air and the temporal bone. The lateral boundary of the middle ear cavity, formed by the very thin tympanic membrane, was not clearly seen as an anatomic structure in most subjects. The position of the tympanic membrane is marked by 2 small bony projections of increased bony density along the anterior and posterior walls of the most medial aspect of the external auditory canal. These projections mark the attachments of the tympanic membrane to the auditory canal and were visualized in at least 1 image in all subjects.

Vestibular Apparatus and Cochlea

The Internal Auditory Canal

The critical landmark is the internal auditory canal within the petrous portion of the temporal bone. The internal

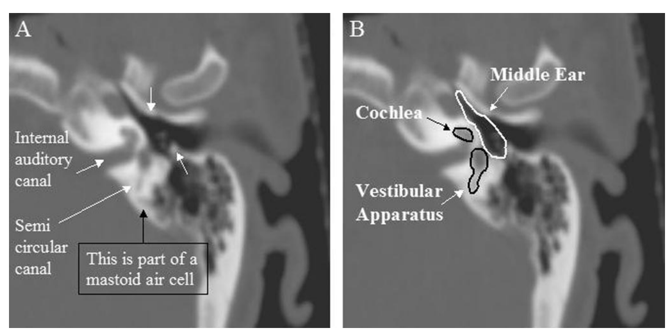


FIGURE 1. Major anatomic landmarks for identifying the cochlea, vestibular apparatus, and middle ear on the axial images of a treatment planning computed tomography scan. The best way to locate the vestibule and cochlea is to first identify the internal auditory canal. The image on the left (A) shows the anatomy of the temporal bone at the level of the inner ear without outlines of auditory structures. Important landmarks on this image are the internal auditory canal, the semicircular canals of the vestibular apparatus, and the bony prominences that mark the attachment of the tympanic membrane (unmarked arrows). The image on the right (B) differs from that in (A) only by the addition of contours of the cochlea, vestibular apparatus, and middle ear. Note that portions of a mastoid air cell may look similar to a semicircular canal.

TABLE 1. Mean Volume of the Inner and Middle Ear Structures in $cm^{3\dagger}$

	Extended-Head Adult n = 5	Neutral-Head Adult n = 5	Overall Adult n = 10	Prone Child n = 5	All Patients n = 15
Middle ear	0.56 (0.50–0.63)*	0.55 (0.40–0.77)	0.56 (0.40–0.77)	0.61 (0.40–0.80)	0.58 (0.40–0.80)
Vestibular apparatus	0.48 (0.25–0.60)	0.44 (0.36–0.51)	0.46 (0.25–0.60)	0.41 (0.29–0.56)	0.44 (0.25–0.60)
Cochlea	0.16 (0.12–0.23)	0.14 (0.10–0.17)	0.15 (0.10–0.23)	0.13 (0.11–0.15)	0.14 (0.10–0.23)

*Ranges are in parenthesis.
†All volumes in this table are Organ At Risk Volumes and therefore do not take into account setup uncertainty. See text.

auditory canal was clearly identified in all subjects. The cochlea and vestibular apparatus are well visualized near the most lateral extent of the internal auditory canal.

The plane of the internal auditory canal is the landmark that distinguishes the cochlea from the vestibular apparatus. In all projections, the vestibular apparatus is located posterior to the plane of the auditory canal and the cochlea is located anterior to the plane of the internal auditory canal. The semicircular canals of the vestibular apparatus and spiral canals of the cochlea appear as small curved or round lucencies within the temporal bone.

Reference Values for the Volume and Maximum Axial Dimension of the Middle ear, Vestibular Apparatus, and Cochlea

Table 1 presents the results of the volume calculations for the middle ear, vestibular apparatus, and cochlea. Head position (neutral vs. extended) and age (adult vs. child) had no significant effect on the volume for each of the 3 structures. In terms of size, the middle ear was the largest structure, followed by the vestibular apparatus and then cochlea. The middle ear and vestibular apparatus are similar in size (overall mean volumes 0.58 and 0.44 cm^3, respectively). The cochlea is approximately one third the size of the vestibular apparatus (overall mean volumes 0.14 and 0.44 cm^3, respectively).

Table 2 presents the results of the maximum axial dimension measurements. The maximum distance across the contour averaged 1.57 cm for the middle ear, 1.10 cm for the vestibular apparatus, and 0.69 cm for the cochlea.

A Reference Atlas for Contouring the Middle Ear, Vestibular Apparatus, and Cochlea

Figure 2 presents a series of 5 images that serve as a reference atlas for contouring the auditory structures on radiotherapy planning scans.

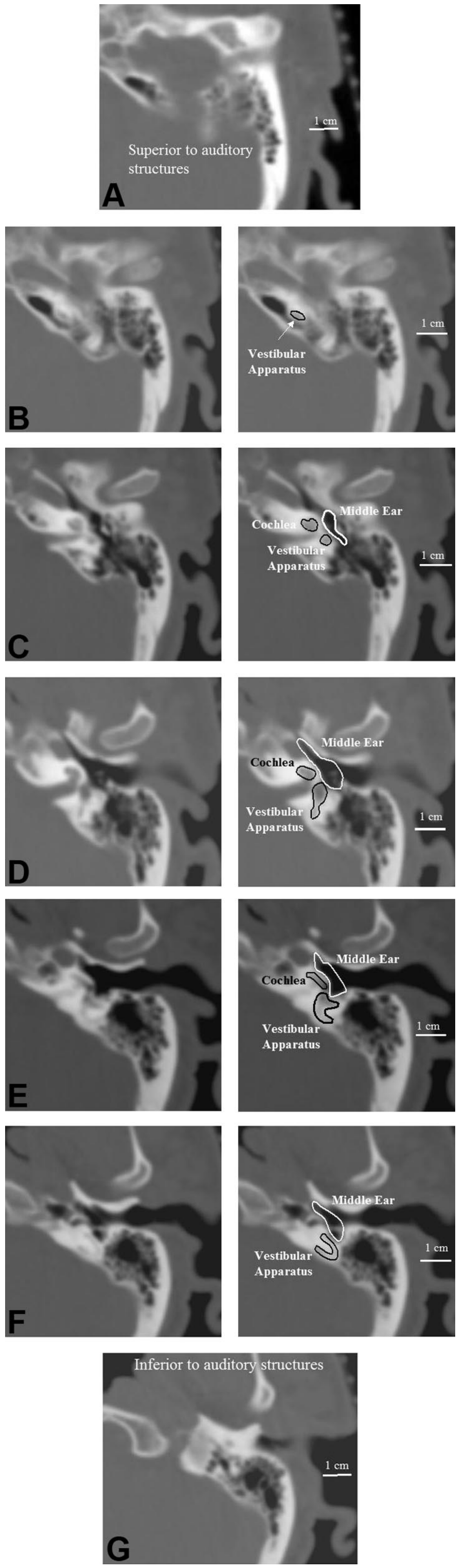
DISCUSSION

To our knowledge, this article is currently the only publication that is specifically designed to help radiation oncologists contour middle and inner ear structures on treatment planning scans. There are many books and articles that describe the radiographic anatomy of the auditory and vestibular apparatus. These articles and books most commonly provide detailed anatomic information as seen on thin section CT images (of $\leq$1 mm slice thickness) performed with a small field of view (of $\leq$9 cm). Currently, such imaging parameters are not used for radiation therapy treatment planning scans leaving uncertainty if and how clearly the middle ear cavity and inner ear structures can be seen on treatment planning scans. The conclusion of both the radiation oncologists and neuroradiologist involved with this project is that it was possible to identify the location of the cochlea and vestibular apparatus on our treatment planning scans with a degree of accuracy that is acceptable for most radiation therapy situations.

TABLE 2. Mean Maximum Axial Dimension of the Inner and Middle Ear Structures in cm†

	Extended-Head Adult n = 5	Neutral-Head Adult n = 5	Overall Adult n = 10	Prone Child n = 5	All Patients n = 15
Middle ear	1.66 (1.45–2.02)*	1.54 (1.24–1.99)	1.60 (1.24–2.02)	1.50 (1.08–2.19)	1.57 (1.08–2.19)
Vestibular apparatus	1.15 (0.90–1.42)	1.08 (0.90–1.35)	1.12 (0.90–1.42)	1.07 (0.84–1.24)	1.10 (0.84–1.42)
Cochlea	0.65 (0.57–0.72)	0.78 (0.62–1.00)	0.72 (0.57–1.00)	0.63 (0.55–0.69)	0.69 (0.55–1.00)

*Ranges are in parenthesis.
†All measurements in this table are for Organ At Risk Volumes and therefore do not take into account setup uncertainty. See text.



Radiation oncologists from the University of Michigan, Baylor College of Medicine and Loma Linda University have published papers that suggest that noncoplanar field arrangements, IMRT, and proton beam therapy can produce dose distributions in patients with posterior fossa medulloblastoma that spare the inner ear to a degree that is not possible with conventional radiotherapy techniques.[1,4,10] Each of these papers contains figures that show a contour of some portion of the inner ear superimposed on a single CT scan slice. The clarity and magnification of the scan images is not sufficient to serve as a reference atlas. The authors do not describe the anatomic landmarks that were used to guide the contouring process. Most papers contour only the cochlea. Volume and size parameters are not presented.

It is important for the radiation oncologist to have reference values for the approximate size of the structures they are trying to contour. Three-dimensional volume is the most accurate measurement of size, but it is also useful to have a 2-dimensional measurement to guide contouring on axial images. Therefore, we measured the maximum size of the contour of each of the structures of interest in the axial plane. It is important to note that all contours shown and discussed in this article, and all volume and dimension results, refer to the "Organ At Risk Volume" as defined by ICRU report 62.[8] When planning radiotherapy treatment, it is usually appropriate to expand normal structure contours in the skull by a 2- to 5-mm margin to take into account daily setup uncertainty.

This project did not attempt to identify the optimal window setting for contouring auditory structures on planning scans. There is no question that bone window settings are better than settings used to view soft tissue structures. It is not possible to give an exact window setting recommendation because image contrast varies to some degree for each scanner independent of window setting. When contouring auditory structures, our general recommendation is to use a window width of 3000 to 4500 and a window level of 400 to 800.

In this project, we did not contour the nerves that are responsible for hearing and balance. If one wanted to contour the path of the eighth cranial nerve between the brain stem

FIGURE 2. Reference atlas for contouring the middle ear, vestibular apparatus, and cochlea on a treatment planning computed tomography scan. In this example, the patient is an adult with the head in the neutral position (mandible vertical) and the slice interval is 3 mm. The images go from superior to inferior as the labeling letters go from (A) to (G). On the most superior and inferior images, none of the auditory structures are visualized. The cochlea (black contour), vestibular apparatus (black contour), and middle ear (white contour) are outlined on images (B) through (F).

and inner ear, the internal auditory canal is an excellent surrogate for this on a CT scan. The branches of the auditory nerve that supply the cochlea (cochlear nerve) and vestibular apparatus (superior and inferior vestibular nerves) are not visualized on a CT scan. These nerves are located within the structures that they innervate so contouring inner ear structures as described in this article includes the associated nerves.

An important issue that was not addressed in detail in our project is the importance of slice thickness of the CT images. Our results are based on a slice thickness of 3 mm in the 10 adult patients and 5 mm in the 5 children because this was the scan protocol in our department. When the dose to a structure in the inner or middle ear is going to be an important factor in determining the quality of the radiotherapy plan, it would be ideal to perform the planning scan with a slice interval of 1 mm through the temporal bone. The publications that correlate inner ear dose with hearing loss express results in terms of the mean dose to the cochlea.[1,4,9,10] Mean dose depends on overall volume so more detailed scanning will likely change dose-volume histogram parameters. The recent introduction of multislice CT scanners with a major reduction in acquisition time despite utilization of submillimeter slice thickness will certainly revolutionize the quality of the radiation therapy scans in the near future. Currently, most diagnostic radiology departments do not have multislice CT scanners so it is likely to be many years before this technology is routinely used in radiation oncology. In the absence of this new technology, our policy is to use a slice interval of 3 mm in all cases in which sparing of the inner or middle ear is an important planning objective.

CONCLUSION

As immobilization, setup verification, and dose delivery systems continue to improve, radiation oncologists will focus more attention on treatment plans that produce a steep dose falloff over portions of the middle or inner ear when treating patients with tumors near the temporal bone. To improve the therapeutic ratio of radiotherapy in this situation, it is essential to be able to contour the 3 major components of the auditory and vestibular apparatus as accurately as possible on the kinds of scans that are routinely used in radiotherapy planning. The available data currently suggest that hearing loss occurs in a dose-dependent fashion over the range of doses used to treat cancer.[1,9] As we learn more about the radiation tolerance of the organs that control hearing and balance, it will become important to contour the middle ear, cochlea, and vestibular apparatus as separate structures. The information presented in this article is organized to facilitate this task.

REFERENCES

1. Huang E, Teh BS, Strother DR, et al. Intensity-modulated radiation therapy for pediatric medulloblastoma: early report on the reduction of ototoxicity. *Int J Radiat Oncol Biol Phys*. 2002;52:599–605.
2. Jereczek-Fossa BA, Zarowski A, Milani F, et al. Radiotherapy-induced ear toxicity. *Cancer Treatment Reviews*. 2003;29:417–430.
3. Linskey ME, Johnstone PAS. Radiation tolerance of normal temporal bone structures: implications for gamma knife stereotactic radiosurgery. *Int J Radiat Oncol Biol Phys*. 2003;57:196–200.
4. Lin R, Hug EB, Schaefer RA, et al. Conformal proton radiation therapy of the posterior fossa: a study comparing protons with three-dimensional planned photons in limiting dose to auditory structures. *Int J Radiat Oncol Biol Phys*. 2000;48:1219–1226.
5. Swartz JD, Harnsberger HR. *Imaging of the Temporal Bone*, 3rd ed. *The Middle Ear and Mastoid*. New York: Thieme Medical Publishers, Inc; 1998:47–169.
6. Jinkins, JR. *Atlas of Neuroradiologic Embryology, Anatomy, and Variants*, 1st ed. *Cranium*. Philadelphia: Lippincott Williams & Wilkins; 2000:62–414 (Skull Base 86–119).
7. Linskey ME, Joshnstone PAS, O'Leary M, et al. Radiation exposure of normal temporal bone structures during stereotactically guided gamma knife surgery for vestibular schwannomas. *J Neurosurg*. 2003;98:800–806.
8. International Commission on Radiation Units and Measurements. Prescribing, recording and reporting photon beam therapy (supplement to ICRU Report 50). Bethesda, MD: ICRU Report 62; 1999.
9. Kileny PR, Pan CC, Snorrason RM, et al. A prospective study of hearing loss and inner ear dose in irradiated head and neck cancer patients. *Int J Radiat Oncol Biol Phys*. 2003;57:S301.
10. Fukunaga-Johnson N, Sandler HM, Marsh R, et al. The use of 3D conformal radiotherapy (3D CRT) to spare the cochlea in patients with medulloblastoma. *Int J Radiat Oncol Biol Phys*. 1998;41:77–82.