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Abstract

Introduction: Stereotactic radiosurgery (SRS) is increasingly used as a minimally invasive alternative in many neurosurgical conditions, including benign and malignant tumors, vascular malformations, and functional procedures. As for any surgical procedure, strict safety guidelines and checklists are necessary to avoid errors and the inherent unnecessary complications. With regards to the former, other groups have already reported human and/or technical errors. We describe our safety checklist for Gamma Knife radiosurgical procedures.

Methods: We describe our checklist protocol after an experience gained over 1500 radiosurgical procedures, using Gamma Knife radiosurgery, performed over a period of 8 years, while employing the same list of items. Minor implementation has been performed over time to address some safety issues that could be improved.

Results: Two type of checklist are displayed. One is related to the indications when a specific tissue volume is irradiated, including tumors or vascular disorders. The second corresponds to functional disorders, such as when the dose is prescribed to one specific point. Using these checklists, no human error had been reported during the past 8 years of practice in our institution.

Conclusion: The use of a safety checklist for SRS procedures promotes a zero-tolerance attitude for errors. This can lower the complications, and is of major help in promoting multidisciplinary cooperation. We highly recommend the use of such tool, especially in the context of the increase use of SRS in the neurosurgical field.

Key words: stereotactic, radiosurgery, Gamma Knife, medical physics, checklist, safety

INTRODUCTION

Stereotactic radiosurgery (SRS) was developed by the Swedish neurosurgeon Lars Leksell at the beginning of the 1950s[14] and defined as the "delivery of a single, high dose of ionizing radiation to a small and critically located intracranial volume through the intact skull"[14]. Initially, Leksell considered SRS as a primary tool in functional neurosurgery[14, 15]. In fact, as early as 1951, he treated a patient with trigeminal neuralgia using a prototype guiding-device linked to a dental X-ray machine[14]. The word "stereotactic" is frequently employed in conjunction with radiosurgery, as "stereotactic radiosurgery" and refers to a three-dimensional coordinate system. The former allows accurate correlation of a virtual target, seen in the patient's therapeutic images, with the actual target position in the patient. The principle of this device was to irradiate an intracranial target with narrow beams of radiation from multiple directions. The beam paths further converges in the target volume, distributing a desired cumulative dose of radiation, while reducing the dose to the adjacent healthy tissue, to obtain a desired radiobiological effect, which might differ according to the treated pathological condition.

In 1968 Leksell created the Gamma Knife (GK), a tool for SRS using multiple focusing cobalt-60 sources[15]. Gamma Knife radiosurgery (GKRS) is a neurosurgical frame-based stereotactic procedure, combining image guidance with high-precision convergence of multiple gamma rays, emitted by 192 sources of Cobalt-60 in its latest versions (Leksell Gamma Knife® (LGK) Perfexion™ and ICON™, Elekta Instruments, AB, Stockholm, Sweden)[33]. Moreover, SRS using LGK ICON™ also allows for frameless radiosurgery using a mask instead of a stereotactic frame while performing single fraction or hypofractionnated radiosurgery in well-selected cases[33]. Nowadays, the clinical applications of GKRS include benign and malignant tumors of the brain and skull-base[6, 8, 20, 34], vascular malformations[9, 21], functional[11, 12, 24, 36] and psychiatric[25] disorders. The intimate mechanisms of action may differ according to the treated condition and the targeting strategy: tumors - apoptosis[27-29]; vascular malformations - vessels obliteration by thrombotic endothelial proliferation[30-32]; functional procedures - targeting a specific anatomical point in an anatomical structure (e.g. thalamus[35, 38], anterior limb of the internal capsule[10], trigeminal nerve[13, 16, 23]) or targeting a larger zone, such as an epileptic focus[1, 22].

The use of SRS in clinical practice has expanded over the past decade. This includes both first line procedures, as well as in recurrence cases, or in combination with microsurgery, in the framework of combined approaches[3, 26].

The introduction of our GKRS activity in Lausanne in July 2010 has made necessary the introduction of a safety checklist, to avoid unpleasant radiosurgical events, as previously reported by others[2]. The former has been created as early as the first treated patient, as a need for the medical physics and neurosurgical teams to initially have a standardized tool to evaluate GKRS planning. This list has been further adapted to new type of indications (e.g. functional procedures) and procedures (e.g. hypofractionated treatments), as well as benefited from minor implementation to address some safety issues that could be improved.

METHODS

The Lausanne radiosurgery equipment in the neurosurgical setting

In 2010, our hospital acquired the LGK Perfexion™ that was upgraded and commissioned[39] to LGK ICON™in 2016 . Our activity remains frame-based in a vast majority of cases (see below).

Radiosurgery steps with LGK

For SRS procedures, the first step is the fixation of Leksell G stereotactic frame, under local anesthesia. The exceptions to this step are: 1- hypofractionnated procedures or 2- single fraction procedures in some specific conditions allowing for more tolerance in target accuracy (e.g. recurrence in a surgical cavity, target far from organs at risk and eloquent brain areas), where a thermoplastic mask is considered. The second step is stereotactic neuroimaging (both MRI and CT). The third step is performed into the Leksell GammaPlan® planning software (LGP, Elekta Instruments, AB, Stockholm, Sweden), starting with the registration of the stereotactic images and further with the radiosurgical dosimetry planning. The fourth step is treatment delivery itself.

IRB/ethics committee approval

As this is a single theoretical and hypothetical case study, including no patients' data, IRB approval is not required. Furthermore, patient consent is not required as there are no clinical data presented here.

Construction of the checklist

The first draft of the Lausanne checklist was created in 2010, as a joint effort between the medical physics and neurosurgical teams. The original intention was to have a standardized and common tool to evaluate the safety and efficacy of GKRS planning. This has been further developed to accommodate specific issues (such as those related to functional procedures, whose reimbursement was approved in 2012), technical advances (such as the hypofractionnation with LGK ICON™ in 2016), and also benefited from minor implementations to address the occurence of more common errors (including name misspelling, date of birth mistakes etc), or additional necessary items for new indications, that were not including in the original checklist (the integral dose to the nerve in trigeminal neuralgia, etc).

Basis of the checklist

The main items include: *1- basic demographic features*, abling to identify patients at any moment during the clinical workflow, while interrogating the database : the name, date of birth and the personal ID within the global identification system of the hospital ; *2- data related to the diagnosis* (type of indication, first intention radiosurgery versus other type, previous treatments) ; *3- data related to dose prescription, number of fractions and dose per fraction ; 4- frame-based versus frameless treatment ; 5- specific dosimetric parameters* (target volume, coverage, prescription isodose volume, doses to organs at risk, etc) ; *6- beam-on time and total treatment time ; 7- number of isocenters used and their delivery workflow (specific to LGK);; 8- dose rate (specific to LGK)*

Objectives of the checklist

The complications that the checklist aims to avoid are those resulting from common and major errors in SRS, either related to the patient or related to the dosimetry.

Moreover, since running the checklist ensures that the collection of information related to the patient and its condition are correctly recorded, it also helps to avoid mistakes when storing those information in the database for further clinical and scientific use.

I. Risks of errors related to the patient

a- Confusion or mix-up of a patient's diagnosis: this starts back with the frame application. We usually print one image displaying the patient's pathology, lesion, or target area (in functional procedures, specific care is taken to the side of the target area). We further verify the name on the printed image, and crosscheck it with the medical and the nursing files, and during direct interaction with the patient before frame application (we also crosscheck the name of the patient on the hospital admission wristband).

b- Substitution of a patient by another at the time of installation in the gamma knife: this is of particular importance, as we frequently treat an average of 3 patients per day. In Switzerland, common names, such as « Pasche », written with « sch », « ch » or other variants may lead to confusions. We check the patient's admission wristband, and ensure correspondence with her/his name and date of birth, as appearing on the treatment screen. We also check for the patient's personal information in the checklist, ensuring that they are correctly entered into LGP and that they will display correctly on the treatment screen.

c- Encoding and treating for a wrong diagnosis is a major and potential catastrophic issue, as it may affect significantly the dose prescription. For example, treating for an AVM in a patient with another type of lesion in the primary motor cortex would potentially cause irreversible hemiplegia. Therefore, we check for the diagnosis and for the dose prescription in the checklist.

d- Side (left/right) confusion for unilateral disease in functional procedures, such as trigeminal neuralgia or unilateral thalamotomy for tremor, is also a risk with major consequences. Therefore, thepatient is asked to say, 3 times during the day, including before the installation in gamma knife, which side is affcted. This is further confronted with the X value (left/right) of the stereotactic coordinates, as displayed by LGP in the treatment protocol.

II. Risks of errors related to the dosimetry

a- Dose prescription: errors of dose prescription may catastrophic consequences. Avoidance of such errors is of particular importance in functional procedures, in which very high doses of radiation are prescribed (e.g. 130 Gy in the ventro-intermediate nucleus of the thalamus for tremor, 70-90 Gy in in the cisternal part of the trigeminal nerve, close to the brainstem, in trigeminal neuralgia) at a specific

coordinate point (i.e. at the 100% isodose line). Thus, confusion in isodose line prescription is a possible error with major consequence. For instance, prescribing at the 50% isodose line while keeping the radiation dose at 130 Gy will double what is already an important amount of radiation. Thus, both the dose and the isodose prescription (as well as the consequent maximal dose) are checked several time in the validation process.

b- Number of fractions and dose per fraction may lead to errors, mainly in confusion between the total dose and dose per fraction.: For instance, aiming at prescribing 25 Gy in 5 fractions f(i.e. 5 Gy/fraction), shold not mistakenly become prescribing 25 Gy per fraction in 5 fractions (i.e. 5 times more per fraction) for the same pathology. Thus in hypofractionated treatments, this issue has been implemented in the checklist.

c- Errors in the arget volume, prescription isodose volumes, coverage of the lesion, etc. are mainly reflected in the conformity, selectivity and gradient indexes. These indexes are calculated in the checklist and compared with the values provided in LGP. Any mismatch between these values are checked and carefully analyzed. Moreover, values which are overpassing what is considered classical as ranges for the radiosurgical indexes[5, 17-19], are to be explained and justifyed, and/or verified.

d- Organs at risk: some are straightforward, like the cochlea in a vestibular schwannoma cases; however, one might be treating a lesion closed to the optic apparatus, without necessarily make a dedicated MR sequence to visualize it properly and evaluate the dose received by the former. The same would apply to the pituitary stalk in a cavernous sinus lesions, for example, the brainstem in trigeminal neuralgia cases, etc. Moreover, as a routine, we also recommend to chek the dose to the lenses, and avoid direct beams through them to avoid an increased risk of cataract.

e- Other issues specific to ensure LGK treatment quality and safety are included in the checklist, such as the correct grid size for dose calculation, the verification that shots positioning may not be at risk of collision into the gamma knife, recalculation and check of the dose rate, etc …

Use of the checklist

We have made the use of the checklist a mandatory document for every LGK treated patient in our institution. The physicist is in charge of completing the checklist, first based items from the patient's hospital file or by calculating values, and then "interrogates" the neurosurgeon about each item of the list. The neurosurgeon "answers" to the physicist in

providing him/her with the items or values that have been entered, or that are displayed, in LGP. When a mismatched information or an unexpected value is observed, the specific item is verified and clarified (i.e. corrected or specifically justified, if accepted as such). Only when the checklist has been fully verified, the treatment planning is approved in LGP and is exported to the LGK console, and the treatment delivery is performed.

Thus, the checklist *per se* is used at the time of dosimetry planning validation and approval, but it also encompass items that are involved earlier in the workflow (i.e. at the time of frame placement and image acquisition) and at the time of positioning of the patient into the gamma knife for treatment, as described above.

RESULTS

Since the introduction of the GKRS activity in Lausanne in June 2010, over 1500 patients had been treated. The safety checklist had been used in each case. Up to now, no human or machine related error has happened.

There are two main separated checklists, based on a common template. These 2 checklists are different as per the indications they cover, in relation with the respective items they cover: 1- when a target volume is drawn, such as for tumors, arteriovenous malformations etc (table 1, supplementary file 1), the checklist include items with respect to the dosimetry related to the target volume (e.g. dose-volume histograms, coverage, selectivity, etc …); 2- for functional procedures, a target volume is usually not defined, whether the dose is prescribed to one point (at the 100% isodose line), like in trigeminal neuralgia or drug-resistant tremor, or when the dose in prescribed to a larger anatomical structure, like in mesio-temporal lobe epilepsy (table 2, supplementary file 2). Therefore, the checklist does not include items specific to the dosimetry related to the target volumes. In both instances however, dosimetry to organs at risk are checked and verified, according to the anatomical location of the treated target.

Their common part includes the patient's identity information, indication and dose prescription related data (dose, isodose prescription, fraction(s)), registration of the images, frame or mask fixation, geometry of skull and collision aspects, dose-volume histograms to organs at risk, beam-on and total treatment time, and treatment plan final details.

The neurosurgeon and the medical physicist, together with a designated radiation oncologist, validate the checklist in multidisciplinary fashion.

DISCUSSION

The modern GKRS era involves a multidisciplinary coordination, under the supervision of a neurosurgeon, like in our center. Standardized safety checklists ensure the complete and effective communication between several disciplines. They avoid preventable errors in patient's management, increasing the safety and efficacy of the procedures. This further reduces complications, as well as ambiguities in the workflow.

In 2009, the World Health Organization (WHO) published the Surgical Safety Checklist (SCC) as part of a Safe Surgery Saves Lives campaign. The checklist had been adapted from the field of aviation, where the use of such list is standard practice. The WHO considered addressing surgical safety due to the more than 200 million operations performed annually. The initial purpose was to help the operating room teams to remember important details that might have been missed during the interventions. Furthermore, this served as a instrument to inspire teamwork and communication[37].

Although the effect of SRS is not immediate, unlike open microsurgery, its short-, medium- and long-term effects could have major impact, including on patient's lives, if performed in an uncontrolled workflow. Errors have already been reported in the radiosurgery field in 2004 in Florida (Linac calibration error, 77 patients), or later in Toulouse (error in measurement of output factors, 145 patients)[2, 4]. These errors may have clinical impact, such as those described by Gourmelona et al.[7], where 31% of 12-months trigeminal neuropathy were recorded in 32 acoustic neuroma patients overdosed in the Toulouse accident. Particularly, this type of errors impacts on the quality of life of the patients, or can even have life-threatening consequences. For example, a trial involving the University of Ghent in currently ongoing and related in the press, regarding patients that have been mistreated for brain tumors between 2005 and 2006. Misplacement of the stereotactic targeting radiation, sometimes for more than one centimer, has lead to several fatalities. Furthermore, a review of the Nuclear Regulatory Commission (NRC) Radiation Event Report Notification database yielded 13 radiosurgery-related events from 2005 to present, 12 of which were caused by a deviation from the original prescription protocol. Although the patients' outcomes were not particularly described, one could expect significant morbidity. Some of these errors included fiducial boxes not properly installed on the patient's head during CT or MR imaging, targeting the wrong trigeminal nerve in unilateral pain, targeting

the wrong cranial nerve (facial instead of trigeminal), incorrect dose prescription, couch moving during treatment, etc…

Radiosurgery must benefit from specialized technology, meticulous procedures and dedicated personnel. Using a safety checklist has the major advantage of double-check verification with further decrease of human errors, and therefore avoiding unnecessary and preventable toxicity. In our setting, the neurosurgeons, the medical physicists, together with the radiation oncologist, are validating this checklist for each patient before the start of the irradiation. The use of this checklist is not a time-consuming task, as it takes about10 minutes to run, and it contributes strongly to the patient's safety. The checklist also contributes to the comfort of the SRS team since it ensures a higher level of confidence in the quality of the treatments applied.

Table 1: Safety checklist for benign and malignant tumors, arteriovenous malformations etc
Table 2: Safety checklist for functional disorders (mainly trigeminal neuralgia and tremor)

Supplementary file 1: file for tumors, AVM etc
Supplementary file 2: file for functional disorders

Compliance with Ethical Standards:

Funding: This study was funded by Lausanne University Hospital.

Conflict of Interest: The authors report no conflict of interest.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Ethical approval: For this type of study formal consent is not required

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