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A Quality Assurance Method that Utilizes 3D Dosimetry and Facilitates Clinical Interpretation

Mark Oldham, Ph.D.^{*}, Andrew Thomas, Ph.D.^{*}, Jennifer O'Daniel, Ph.D.^{*}, Titania Juang, B.Sc.^{*}, Geoffrey Ibbott, Ph.D.[†], John Adamovics, Ph.D.[‡], and John P. Kirkpatrick, M.D.^{*}

^{*}Radiation Oncology, Duke University Medical Center, Durham, North Carolina

[†]The University of Texas MD Anderson Cancer Center, Houston, Texas

[‡]Rider University, Lawrenceville, New Jersey

Abstract

Purpose—To demonstrate a new three-dimensional (3D) quality assurance (QA) method that provides comprehensive dosimetry verification and facilitates evaluation of the clinical significance of QA data acquired in a phantom. Also to apply the method to investigate the dosimetric efficacy of base-of-skull (BOS) intensity-modulated radiotherapy (IMRT) treatment.

Methods and Materials—Two types of IMRT QA verification plans were created for 6 patients who received BOS IMRT. The first plan enabled conventional 2D planar IMRT QA using the Varian portal dosimetry system. The second plan enabled 3D verification using an anthropomorphic head phantom. In the latter, the 3D dose distribution was measured using the DLOS/Presage dosimetry system (DLOS = Duke Large-field-of-view Optical-CT System, Presage Heuris Pharma, Skillman, NJ), which yielded isotropic 2-mm data throughout the treated volume. In a novel step, measured 3D dose distributions were transformed back to the patient's CT to enable calculation of dose-volume histograms (DVH) and dose overlays. Measured and planned patient DVHs were compared to investigate clinical significance.

Results—Close agreement between measured and calculated dose distributions was observed for all 6 cases. For gamma criteria of 3%, 2 mm, the mean passing rate for portal dosimetry was 96.8% (range, 92.0%–98.9%), compared to 94.9% (range, 90.1%–98.9%) for 3D. There was no clear correlation between 2D and 3D passing rates. Planned and measured dose distributions were evaluated on the patient's anatomy, using DVH and dose overlays. Minor deviations were detected, and the clinical significance of these are presented and discussed.

Conclusions—Two advantages accrue to the methods presented here. First, treatment accuracy is evaluated throughout the whole treated volume, yielding comprehensive verification. Second, the clinical significance of any deviations can be assessed through the generation of DVH curves and dose overlays on the patient's anatomy. The latter step represents an important development that advances the clinical relevance of complex treatment QA.

Keywords

3D dosimetry; IMRT; Quality assurance; Treatment verification

Introduction

A recent report from the Radiological Physics Center (RPC) revealed unacceptably high national failure rates for the head-and-neck intensity-modulated radiotherapy (IMRT) credentialing test (1). During the period from 2001 to 2009, a total of 752 phantom irradiations were analyzed from 472 institutions. Twenty-two percent of institutions failed the credentialing criteria on the first attempt, the majority failed only on dose criterion. The situation is especially concerning considering the generous nature of credentialing criteria. The criteria require that the absolute dose at a few locations in the planning target volumes (PTV) be within 7% of the planned dose and that the midpoint of the steep gradient between PTV and organs at risk be accurate to within 4 mm. Accurate treatment of a static, rigid phantom to within 7% and 4 mm should be well within the capabilities of modern IMRT systems. However, the 22% failure rate described above is certainly a lower estimate due to sparse sampling of the credentialing film and TLD (thermoluminescent dosimeter) measurements. A comprehensive three-dimensional (3D) credentialing test would be expected to find greater deviations (2).

Concerns over the accuracy and implementation of IMRT raised by the RPC data are compounded by a recent report that indicates common methods of patient-specific planar IMRT quality assurance (QA) have no relevance to the prediction of clinical significance of dose errors in the patient (3). Planar per-beam IMRT QA measurements (*e.g.*, portal dosimetry, diode/ion chamber array) routinely yield small deviations between planned and measured fluencies. However the clinical significance to the patient of these deviations cannot easily be interpreted (4). Taking the critical step of understanding the clinical significance of deviations has been shown to be unfeasible with per-beam planar IMRT QA methods.

The present work aimed to investigate the three issues described above in the context of a cohort of 6 patients receiving base-of-skull (BOS) IMRT treatments delivered at our Institution. The first issue, that of determining the accuracy of the IMRT dose delivery, was addressed by the application of a novel, recently commissioned 3D dosimetry system, the Duke large-field-of-view optical computed tomography (CT) scanner (DLOS)/Presage (Heuris Pharma, Skillman, NJ) (2). Three-dimensional dose distributions are measured with isotropic 2-mm resolution throughout the delivered dose distribution. The second issue, that of the relevance of planar IMRT QA techniques, was investigated by comparing the 3D dosimetry analysis with the corresponding regular planar IMRT QA routinely performed with the 2D Varian portal dosimetry system. Consistent passing rates and trends between the 2D and 3D methods would suggest 2D methods are adequate, although no information is provided on the clinical significance of any deviations in the latter. The third and key issue of how to render IMRT QA measurements into clinically meaningful information was addressed by a novel method that transforms the 3D dose measurements in the phantom back to patient CT geometry, thereby enabling generation of clinical QA metrics like dose-volume histograms (DVH) and dose overlays on the patient's anatomy. This last step enabled DLOS/Presage dosimetry system (DLOS=Duke Large-field-of-view Optical-CT System, Presage dosimeters from Heuris Pharma, Skillman, NJ) the clinical significance of any errors determined during the QA delivery to be evaluated.

Therapeutic irradiation of tumors in the skull base is particularly challenging because of the irregular shape of these lesions and the close proximity of multiple critical normal tissues. The therapeutic window for successful irradiation may be narrow (5), and an accurate, high-resolution, quantitative depiction of the radiation dose distribution is essential for generating and selecting an effective and safe treatment plan.

Methods and Materials

Patients

Six patients who had received BOS IMRT treatment were randomly selected retrospectively for this dosimetry study. All data were made anonymous prior to the study, and an overview of key parameters is given in Table 1. Treatments were delivered with a radiosurgery system (Novalis; Brainlab Westchester, IL) commissioned at Duke University in December 2008, and all verification measurements were also made with this machine.

Planar IMRT QA measurements

Routine IMRT QA at our Institution is currently performed with an electronic portal dosimetry system (Varian Medical Systems Inc., CA). In this procedure, a verification plan is created in the Eclipse treatment planning system from each approved treatment plan. In the verification plan, the fluence and leaf sequencing of each beam remains unchanged, but all gantry and collimator angles are reset to zero. The portal dosimetry software then computes the expected 2D fluence map to be measured on the electronic portal-imaging device (EPID) in the absence of the patient. The verification plan is delivered on the treatment machine, and the actual fluence delivered to the EPID is recorded. Subsequent analysis in the portal dosimetry software enables detailed comparison between the measured and the predicted 2D fluence on a per beam basis. Line profiles and fluence difference maps can be created, but the main evaluation is performed by calculating the percentage of points failing the gamma criteria of a 3% dose difference (ΔD) and 3-mm distance-to-agreement (Δd) criteria, or 3%, 2mm. In both cases a 5% fluence threshold was applied such that only EPID detector points receiving at least 5% of the maximum fluence were included in the analysis. Prior to QA, the EPID is calibrated with a known dose so that evaluations may be carried out in absolute mode. Details on establishing a QA program based on EPIDs is available in the literature (6, 7).

3D IMRT QA measurements

Three-dimensional dose measurements were performed with cylindrical Presage (Heuris Pharma) dosimeter inserts (10-cm diameter, 12-cm length), which were compatible with the RPC head-and-neck IMRT credentialing phantom (1, 8). Presage is a polyurethane-based material that changes color when exposed to ionizing radiation, causing an optical density change (ΔOD) for visible light. The radiation-induced ΔOD is proportional to the locally absorbed dose and can be imaged using optical CT (9, 10). Recent studies have shown Presage to be an excellent material for 3D dosimetry (2, 11).

The RPC phantom-dosimeter combination was scanned on a GE Lightspeed X-ray-CT scanner with a high-resolution protocol (1.25-mm slice thickness). A verification treatment plan was then created for each patient by recalculating the patient's original treatment plan using the RPC phantom CT data. The isocenter of the verification plan was positioned centrally in the Presage dosimetry insert to ensure a 3D measurement of the whole distribution would be feasible. Recalculation was performed with the Eclipse planning system using the analytic anisotropy algorithm (AAA) at 2.5-mm³ isotropic resolution with the heterogeneity correction applied. Each verification plan was delivered to the RPC phantom (containing the dosimeter), which was positioned on the treatment couch, using standard simulation techniques (*i.e.*, shifts made from CT_{origin} laser markings). Each plan (except plan HN5, which had high dose/fx) was delivered four times to the phantom in order to get close to ~8 Gy, the optimal dose for the dynamic range of the DLOS system for small treatment volumes.

To obtain the delivered 3D dose distribution, the radiation-induced OD throughout the dosimeter was imaged using the DLOS system. The OD is determined by reconstructing corrected projection images by utilizing parallel beam filtered back-projection as described previously (2). A corrected projection consists of a postirradiation projection that has been divided by the corresponding preirradiation projection to obtain the radiation-induced change. Details are given in Thomas *et al.* (2). Three-dimensional data are acquired through the accumulation of 360 projection images over 360° to meet Nyquist sampling criteria for 2-mm³ isotropic reconstructions. Each pre- and postprojection image was corrected for stray light following the method described in reference (12).

The dose response of Presage is known to be highly linear (11), and the 3D OD distribution was converted to dose by scaling to a point of known absolute dose within the head phantom. This point of known dose was determined by a second delivery to the head phantom, this time incorporating a Presage dosimeter of identical dimensions but containing a central channel for a microion chamber (model CC01; Scanditronix Wellhofer, Bartlett TN). The location of the active volume of the chamber was in the middle of the uniform high-dose treatment region. The absolute 3D dose distribution measured by the DLOS/Presage system was then compared with the calculated distribution from Eclipse by using the CERR (Computational Environment for Radiation Research) analysis tool (13). Measured data were registered to CT data via alignment marks on the phantom. A gamma analysis (6) was performed to determine the agreement between the planned and measured distributions. As with the portal dosimetry analysis, two gamma criteria were used, a 3% dose difference (ΔD) and a 3-mm distance-to-agreement (Δd) criteria and a 3%, 2mm criteria, both with a 5% dose threshold. The outer 5-mm rind of the dosimeter was not included due to loss of superficial data from edge artifacts.

Method to extract clinical metrics from 3D measurements made in phantom

Measured 3D dose distributions provide a substantially more comprehensive evaluation of the accuracy of a treatment delivery than can be achieved by conventional planar verification techniques. However, the clinical significance of any detected errors is very difficult to interpret because the measurement is made in the phantom, divorced from the volumes of interest in the patient. To solve this problem and enable generation of measured DVHs in the patient geometry, we transformed the measured 3D dose distribution in phantom back to the patient CT by using a transformation matrix that accounted for the different geometries and heterogeneities (*i.e.*, between phantom and patient). The transformation matrix was formed by dividing the calculated 3D dose distribution in the phantom by that in the patient. In our initial implementation both distributions were calculated by the commissioned Eclipse planning system, although we note that independence from the planning system could easily be achieved by using a different algorithm. The accuracy with which the transform models differences in attenuation between the phantom and patient geometries is therefore dependent on the similarity of these geometries and the relative accuracy of the Eclipse AAA algorithm in these geometries. Eclipse uses a convolution-superposition algorithm (AAA) which is known to account for these effects well (14). The transformed dose can be overlaid onto the patient's CT data to enable visualization of the measured dose to contoured structures in the patient plan. Comparison of planned and measured DVHs was performed using the CERR tool. The PTV and some of the organs at risk could then be analyzed for clinically relevant differences occurring between the planned and the measured dose data. The transformation matrix is only defined for regions inside the dosimeter, where measurement occurred. If organs extend outside this volume, accurate DVH comparison can be achieved only for that part of the organ within the dosimeter.

Results

Single-point 2D and 3D QA measurements

Table 2 compares results from all three IMRT QA measurement techniques. The mean gamma passing rates for 2D portal dosimetry QA for each of the 6 patient plans are shown. The portal dosimetry software yields a gamma passing value for each beam. The mean passing value over all beams for each plan is given together with the range (minimum-maximum). The dose difference data acquired in the portal dosimetry analysis is considered to reflect absolute dose, because the EPID response is calibrated. The 3D passing gamma rates for all plans are given in Table 2. These rates also reflect absolute dose because the 3D distribution is calibrated to a known dose point determined by the ion chamber (values given in the right-most column in Table 2). Correlation of 3D and 2D passing rates are shown in Figure 1. Gamma calculations for DLOS/Presage data are fully 3D in that a 3D search was made about each point to determine the minimum gamma value. The high quality of the measured 3D dose data in phantom and the agreement with calculated 3D data from Eclipse are shown in Figure 2A and B for the best and worst cases defined by 3D passing rates, HN3 and HN6, respectively. Data for axial, sagittal, and coronal isocentric planes are shown, although the comparison can be visualized in any plane.

Clinical interpretation of QA data

Results of the algorithm used to transform 3D dose data measured in Presage back to the patient's CT data are shown for the best and worst case agreements (defined by 3D passing rate) in Figure 3A and B, respectively. Central axial views are shown of the original patient plan (left panel), and the measured dose after transformation back to the patient CT data (right panel). The circular cutoff of data in the latter reflects the boundary of data collection in the cylindrical Presage dosimeter. The lower panels in Figure 3A and B show the corresponding DVH comparison for structures in the patient CT geometry. In all DVH plots, solid lines represent the calculated dose distribution from Eclipse, and dashed lines represent the transformed measured dose in Presage. Comparisons between planned and measured DVHs for the remaining 4 patients are shown in Figure 4.

Discussion

Accuracy of treatments and correlation of 2D and 3D QA data

Gamma criteria for portal dosimetry in current use for routine IMRT QA analysis at Duke are 3%, 3mm. According to these criteria, high pass rates are observed for both 2D and 3D QA data (Table 2 and Fig. 1), indicating that delivered treatments closely matched planned treatments. From the 2D measurements alone, nothing is known about the magnitude of errors compounding in 3D from multiple beams directions. Small deviations between planned and delivered per-beam fluences are observed at the 3%, 2-mm level (Table 2), and imperfections in gantry, couch, collimator, and leaf motions could further exacerbate these deviations in cumulative 3D distribution. The 3D pass rates from DLOS/Presage are derived from the cumulative distributions and, therefore, do reflect any compounded errors from multiple beams. Gamma calculations for DLOS/Presage are fully 3D, and it might be expected that the 3D passing rates would be slightly higher than those of the 2D for the same criteria because there are additional neighboring points which could meet the criteria. This tendency to increase is balanced both by the inclusion of gantry/couch/collimator tolerance motions and the addition of many more evaluation points in challenging areas of the dose distribution (*e.g.*, penumbra superimposed from multiple gantry angles). For data in Table 2, 5/6 plans have higher 2D passing rates at 3%, 3 mm, reducing to 4/6 at 3%, 2 mm. All plans show 3D passing rates above 95% (at the 3%, 3-mm level), indicating excellent agreement between calculated and measured distributions. It is interesting to note that Figure 1 appears

to show no clear correlation between the 2D and 3D passing rates in this small sample. This observation is consistent with the conclusions of another recent study (3) showing that per-beam planar QA data have little relevance to understanding the clinical significance of deviations. The lower 3D passing rates and greater variability are consistent with the possibility that 3D techniques are more sensitive to the detection of errors and that magnification may occur in 3D, of errors detected in 2D QA methods.

Clinical interpretation of 3D QA data

A key and novel step taken in this work was to transform high-resolution 3D dose distribution measured in the phantom back to the patient CT data, thereby enabling comparison between planned and measured DVHs. In the best case agreement (Fig. 3A, HN3), the organs at risk DVH curves are virtually indistinguishable except for a slight increase in the maximum dose delivered to the optic chiasm. The mean measured PTV dose is slightly higher. In the worst case agreement (Fig. 3B, HN6), the maximum dose delivered to the chiasm is very close to that of the predicted (within 0.5%), but at lower doses, the measured DVH is higher by ~1.4 Gy. The delivered PTV dose is noticeably less homogenous, with larger hot spots and a slight (0.8%) increase in mean PTV dose. For the remaining 4 plans (Fig. 4), the two largest differences are that the measured mean and maximum doses to the Lt cochlea are approximately 5Gy higher in HN1 (Fig. 4A) and that the measured mean doses are approximately 2% to 3% less for the left optic nerve in HN2 (Fig. 4B). The maximum dose in brainstem was determined to be ~2Gy higher than planned for HN4 (Fig 4.B). For HN4 (Fig 4C), the optic chiasm, which was the dose-limiting structure, appeared to receive mean and maximum doses that were approximately 200 cGy lower than those calculated. Clinically, this suggests that an additional fraction of radiation therapy might have been safely added.

While the 3D DVH evaluation method offers a more clinically relevant way to evaluate QA results, it is important to note its limitations. First, the accuracy of the DVH calculation is dependent upon the accuracy of the calibration of Presage to absolute dose. While we have maximized this accuracy by using an ion chamber measurement, this does require a second QA delivery of the treatment. Second, the accuracy of the dose transformation between the phantom CT and patient CT is dependent upon the consistency of the beam paths through each geometry between the modeled and delivery conditions. If an error occurs in the delivered fluence, the transform assumes the modeled beam paths and heterogeneities apply, which is a first-order approximation that will gradually break down with greater magnitude errors and deviations between phantom and patient geometry. Highest accuracy will be achieved when the phantom geometry and irradiation closely match those of the patient. Investigating the performance of the transform in a full range of conditions is the subject of future research. A third limitation is that while a delivery error will be detected with this method, the precise cause of the error may be difficult to determine because of the cumulative nature of the measured 3D distribution. The cause may need to be investigated by other dosimetry approaches.

Conclusions

This paper presents the first comprehensive application of a true 3D dosimetry system to the verification of the accuracy of a complex radiation treatment over a cohort of patients. Three-dimensional dosimetry systems like DLOS/Presage have the potential to change the paradigm of how QA data are used for the verification of advanced radiation treatments. There is mounting evidence that suggests that per-beam planar QA data has little relevance for understanding the clinical significance of the cumulative dose delivery deviations. A new method is presented which enables high-resolution 3D data measured in phantom to be transformed back to the patient geometry for the purpose of comparing planned and

measured DVHs and dose overlays. This comparison can immediately present the clinical significance of any cumulative deviations in cases where the phantom geometry is similar to that of the patient.

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References

1. Ibbott GS. QA in radiation therapy: The RPC perspective. *Journal of Physics: Conference Series*. 2010; 250(1):012001.
2. Thomas A, Newton J, Adamovics J, Oldham M. Commissioning and benchmarking a 3D dosimetry system for clinical use. *Med Phys*. 2011; 38(8):4846–4857. [PubMed: 21928656]
3. Nelms BE, Zhen H, Tome WA. Per-beam, planar IMRT QA passing rates do not predict clinically relevant patient dose errors. *Med Phys*. 2011; 38(2):1037–1044. [PubMed: 21452741]
4. Nelms BE, Simon JA. A survey on planar IMRT QA analysis. *J Appl Clin Med Phys*. 2007; 8(3): 2448. [PubMed: 17712302]
5. Lawrence YR, Li XA, el Naqa I, et al. Radiation dose-volume effects in the brain. *Int J Radiat Oncol Biol Phys*. 2010; 76(Suppl 3):S20–S27. [PubMed: 20171513]
6. Low DA, Moran JM, Dempsey JF, Dong L, Oldham M. Dosimetry tools and techniques for IMRT. *Med Phys*. 2011; 38(3):1313–1338. [PubMed: 21520843]
7. Howell RM, Smith IP, Jarrio CS. Establishing action levels for EPID-based QA for IMRT. *J Appl Clin Med Phys*. 2008; 9(3):2721. [PubMed: 18716584]
8. Sakhalkar H, Sterling D, Adamovics J, Ibbott G, Oldham M. Investigation of the feasibility of relative 3D dosimetry in the radiologic physics center head and neck IMRT phantom using Presage/optical-CT. *Med Phys*. 2009; 36(7):3371–3377. [PubMed: 19673232]
9. Oldham M. 3D dosimetry by optical-CT scanning. *J Phys*. 2006; 56:58–71.
10. Babic S, McNiven A, Battista J, Jordan K. Three-dimensional dosimetry of small megavoltage radiation fields using radiochromic gels and optical CT scanning. *Phys Med Biol*. 2009; 54(8): 2463–2481. [PubMed: 19336848]
11. Sakhalkar HS, Adamovics J, Ibbott G, Oldham M. A comprehensive evaluation of the Presage/optical-CT 3D dosimetry system. *Med Phys*. 2009; 36(1):71–82. [PubMed: 19235375]
12. Thomas A, Newton J, Oldham M. A method to correct for stray light in telecentric optical-CT imaging of radiochromic dosimeters. *Phys Med Biol*. 2011; 56(14):4433–4451. [PubMed: 21719946]
13. Deasy JO, Blanco AI, Clark VH. CERR: A computational environment for radiotherapy research. *Med Phys*. 2003; 30(5):979–985. [PubMed: 12773007]
14. Sterpin E, Tomsej M, De Smedt B, Reynaert N, Vynckier S. Monte carlo evaluation of the AAA treatment planning algorithm in a heterogeneous multilayer phantom and IMRT clinical treatments for an Elekta SL25 linear accelerator. *Med Phys*. 2007; 34(5):1665–1677. [PubMed: 17555248]

Summary

A new 3D quality-assurance (QA) method is presented that facilitates evaluation of the clinical significance of QA data. Two advantages accrue: treatment verification is comprehensive throughout the whole treated volume; and the clinical significance of deviations can be assessed through the generation of dose–volume histogram curves and dose overlays on the patient’s anatomy. Both steps represent developments that advance the clinical relevance of complex treatment QA.

Fig. 1.
Correlation of mean 2D portal dosimetry passing gamma rate with 3D DLOS/Presage passing rates. Gamma calculations are 2D and 3D, respectively. All dose measurements were absolute.

Fig. 2. Isodose overlay comparison (20%, 50%, 80%, 90%, and 95% lines) of the Eclipse-calculated and Presage-measured dose distributions (A) in the case of best agreement (HN3 in Table 2) and (B) in the case of worst agreement (HN6). Original treatment plans were recalculated onto the RPC IMRT credentialing head phantom as shown.

Fig. 3.

Comparison of measured and calculated doses for (A) best case, HN3 plan, and (B) worst case, HN6 plan. In each case, central axial slice views are shown of the original Eclipse treatment plan (upper left panel), the corresponding measured dose when transformed back to the patient CT geometry (upper right panel), and the comparison of planned and measured DVH curves. The dashed circle in the upper right panels indicates the boundary of the Presage dosimeter where measurement data are available.

Fig. 4. Comparison DVH plots; solid lines = eclipse calculation; dashed lines = measured Presage for plans HN1 (A), HN2 (B), HN4 (C), and HN5 (D).

Study cases

Table 1

Patient	Disease	PTV volume (cm ³) (equivalent diameter [cm])	No. of IMRT beams	Noncoplanar	Key organs at risk	Dose prescription
HN1	Lt acoustic neuroma	4.28 (2.0)	7	Yes	BS, Ch, ON, cochlea	180 cGy × 28 fx = 5,040 cGy
HN2	Meningioma	29.42 (3.8)	6	Yes	BS, Ch, ON, MO	180 cGy × 28 fx = 5,040 cGy
HN3	ON meningioma	4.37 (2.0)	5	Yes	BS, Ch, ON	180 cGy × 29 fx = 5,220 cGy
HN4	meningioma	46.18 (4.5)	9	Yes	BS, Ch, ON, MO	180 cGy × 30 fx = 5,400 cGy
HN5	Lt cav sinus meningioma	5.2 (2.1)	7	Yes	BS, Ch, ON	1250 cGy × 1 fx = 1,250 cGy
HN6	Lt schwannoma	7.61 (2.4)	7	Yes	BS, Ch, ON, schwannoma	180 cGy × 28 fx = 5,040 cGy

Abbreviations: BS = brainstem; cav = cavernous; Ch = chiasm; fx = fractions; Lt = left; MO = medulla oblongata; ON = optic nerve.

Table 2

Summary of point, 2D, and 3D IMRT QA verification results

Plan	PTV cm ³	Mean portal dosimetry (3%, 3 mm) (range)	Mean portal dosimetry (3%, 2 mm) (range)	DLOS/Presage (3%, 3 mm)	DLOS/Presage (3%, 2 mm)	Ion chamber plan/measured
HN1	4.28	99.7 (99.2–99.9)	98.9 (97.9–99.4)	98.5	93.9	–0.2%
HN2	29.42	98.8 (97.9–99.7)	92 (84.7–96.6)	98.1	97.2	0.3%
HN3	1.98	97.9 (97.2–98.5)	97.2 (96.1–97.9)	99.7	98.9	1.1%
HN4	46.18	99.4 (98.9–99.8)	98.4 (95.3–99.8)	96.5	93.1	–0.9%
HN5	9.36	98.9 (97.9–99.4)	97.6 (97.1–98.6)	98.7	96.0	–0.5%
HN6	7.61	98.2 (96.0–99.2)	96.8 (93.7–98.4)	95.7	90.1	0.3%