Received:
26 August 2015

Revised:
11 January 2016

Accepted:
13 January 2016

doi: 10.1259/bjr.20150709

Cite this article as:

Mills JA, Colligan SJ. Megavoltage quality control, resources and demand: a pragmatic review. *Br J Radiol* 2016; **89**: 20150709.

FULL PAPER

Megavoltage quality control, resources and demand: a pragmatic review

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Objective: Satisfactory radiotherapy treatment requires quality control (QC) of the equipment as well as patient-specific checks. Increased complexity and extended use of equipment plus greater demand for complex treatment has brought pressure on QC resources. The benefits of integrating patient-specific checks and QC and the efficient use of resources is examined.

Methods: A non-linear model for the probability of undetected machine failure is proposed which enables the comparative efficiency of resource to be assessed. Benefits of adopting an integrated view of patient-specific and treatment machine QC is considered, considering performance tolerance levels in the context of measurement uncertainty and patient-specific tolerances.

Results: Essential, machine-only QC is identified. A realistic approach to equipment-only QC is identified for 70% efficient use of resources and a relationship established to determine resource required for a QC programme. Integration of patient-specific and equipment QC is shown to half the resource required for equipment QC.

Conclusion: Increasing benefit from QC requires greater resource, working at lower efficiency. A pragmatic approach is having guaranteed checks supplemented with additional, non-guaranteed checks performed within an integrated approach to machine- and patient-specific QC, bearing in mind the occasions when machine-only QC is essential.

Advances in knowledge: The work reveals on a quantitative basis a rational approach to accommodating the QC requirements for safe and effective treatment.

INTRODUCTION

Quality control (QC) endeavours to demonstrate that adequate performance is being obtained by a system. This is complemented by the ability to use the results of the measurements which are made to initiate corrective action when performance falls below set levels which are considered adequate. In 1975, the safety requirements considered by the Radiotherapy Advisory Safety Measures Panel in the UK were in effect the precursor for elements of the safety standard¹ published by the British Standards Institute concerning megavoltage accelerators' safety. That standard¹ made a significant contribution to the international safety standard.²

Alongside the safety standard¹ came a performance standard, providing a framework for the specification of all the radiation beam characteristics for megavoltage accelerator machines. Although these were started in the UK National Committee of the British Standards Institute, with contributions from other such committees across the world through the International Electrotechnical Commission (IEC) we now have performance standards IEC976³ and IEC977⁴ to sit alongside the international safety standard.²

These documents^{2–4} stand out amongst the QC documents which have been developed by national and other radiotherapy physics organisations. The examples of documents from organizations such as the American Association of Physicists in Medicine,^{5,6} International Atomic Energy Agency/World Health Organization⁷ and Institute of Physics and Engineering in Medicine⁸ serve to emphasize the relevance which QC is considered to have as an essential aspect of safe and effective treatment delivery. However, the IEC documents^{2–4} were developed through the international agreement of what would provide relevant and effective QC. In addition to specifying essential tests for manufacturers to undertake as part of their design and development process, referred to as type tests, the documents provide guidance regarding the site tests required by users. The ongoing performance of the equipment is demonstrated to be adequate through routine tests, as well as ensuring adequate performance has been obtained following installation, repair and adjustment.

In Europe, the essential need for QC and QC programmes has been recognized in an European Commission Directive⁹ concerned with the safety of the patient. This sets

out the need for adequate testing of the equipment prior to treatment; following installation, following machine repair or adjustment and on a routine regular basis. The International Standards Organisation documents support this by providing the standards within which these tests can be undertaken.

It is noticeable in the above that the QC relates to the performance of the machine, an accurate measure of what the machine is designed and therefore expected to perform. It is not concerned with what the machine actually performs, or rather what is delivered to the patient. However, owing to the complexity of more dynamic, modulated and image-guided radiotherapy treatment, treatment simulation measurements have become extremely relevant in order to satisfy the requirements of the EC Directive⁹ with regard to patient safety.

The other significant aspect in implementing and maintaining QC is the increasing demand for treatment and hence machine availability, the increasing demand for complex treatments and hence for complex machines. This is reflected in guidance documents such as national radiotherapy development plans¹⁰ and has led to significant pressure to utilize equipment over extended treatment days^{11,12} and, together with machine complexity, the resource requirements to provide QC is becoming increasingly challenging.¹³ Studies^{14–16} have looked in detail at the increased resource requirement for manpower to implement more complex treatment delivery systems such as intensity-modulated radiotherapy treatment. Although there is recognition in these for increased QC, no practical solution is addressed. Indeed in the Scottish report,¹² it is simply assigned to non-clinical time. At some stage, it would be prudent for the radiotherapy physics community to take an objective approach to optimally rationalizing the QC on these machines.

This article presents a rationale to maximize the benefit of QC with limited resources. With increasing treatment complexity, it also considers the balance between machine performance QC as outlined in the Standards and the essential need to verify accurate treatment delivery on a patient-specific basis and on how this balance can reduce the demand on resources.

QUALITY CONTROL DEFINITIONS AND SCOPE

A machine failure can be considered to be of two types; firstly, a component or a system breakdown or, secondly, a change in a systems' operation which alters the performance by an unacceptable amount. Either of these can cause deterioration in performance. Such machine failures can take many forms within the complex systems of a treatment machine.

It is intuitively acceptable to consider that the use of routine QC will diminish the probability of undetected machine failure (PUMF). Without any checks, undetected machine failure is certain, and therefore would have a probability of 1.0. Implementation of QC will reduce this although the amount by which it is brought down from 1.0 will depend upon the types of QC tests performed, the frequency of the test and the technique used for the test.

Despite the use of routine QC, we also know that there is a background level of machine failure which is impossible to

reduce.¹⁷ This background is due to unforeseen disasters such as severe and unpredictable component failure or even human error.

The variation of the probability (p_M) of undetected machine failure with increasing QC is not explicitly known. However, a non-linear form which showed a diminishing return as the number of QC checks increased linearly would be a prudent assumption (Figure 1). This variation shows a diminishing decrease down to the background level mentioned above.

Figure 1 should be considered to represent an ideal variation which assumes that the QC checks are explicitly known, that they are carried out in the most effective manner, at the ideal frequency and with the ideal tolerances to provide the maximum benefit from the check.

It is worthwhile reflecting on this point that QC performs two functions. It detects machine faults and it demonstrates no machine faults. These are two parts of the same distribution, inextricably linked and complimenting each other. One cannot be achieved without the other.

The QC which has historically developed with regard to megavoltage machines has ensured that the equipment can perform adequately to deliver a treatment beam with a specific performance. The tests take place prospectively with regard to the clinical use of the machine. Although it provides assurance that the machine can perform to set standards it does not demonstrate that it has. It is perhaps akin to the QC of a bullet. The bullet may conform to a standard but this is not a check on what the bullet achieves when used.

Demonstration of machine performance and potential to deliver treatment accurately is prospective QC (PQC).

The limitations of PQC became apparent with the increasing complexity of treatment machines. For example, when multileaf collimators (MLCs) were first introduced, they presented a daunting challenge as to how to check their operation within a prospective framework. Prior to MLCs, radiation field sizes

Figure 1. Variation of probability of undetected machine failure (PUMF) as the number of quality control items increases.

had typically been checked with a sequence of square fields. It was impossible to simulate in any meaningful way the infinite combinations of field shapes which were possible with an MLC. The only way to perform checks across the range of MLC shapes was to use the clinical range being treated; in effect to perform a field shape check specific to each patient. This was patient-specific QC (PSQC). As dynamic therapy involving MLC shape, MLC movement, gantry rotation and even dose-rate modulation was introduced, treatment delivery by checking machine performance could not be realistically performed prospectively and the essential need for PSQC was established.

PSQC is performed on the basis of an acceptable dose variation between desired and delivered. This can take any form, but the gamma index¹⁸ is widely used and sets the tolerance criteria for position and dose variation. On the basis of this type of assessment, the operation of specific machine parameters such as flatness or dose linearity are lost within the overall treatment delivery and simply the end point is verified. Specific machine parameters have no consequence unless they impact detrimentally upon the delivery of the treatment. It could be argued then that providing users have confidence in the treatment being delivered through PSQC, assessment of individual machine parameters is not required.

However, as outlined in the EC Directive,⁹ PQC is required for many instances. These have also been encompassed within the Ionising Radiation Regulations 2000 in the UK¹⁹ and are as follows:

- (1). following installation of a machine, acceptance requires testing to ensure that the specification has been met
- (2). post repair, it is necessary to ensure that the performance has been restored
- (3). post intervention such as beam control adjustment to ensure performance is restored
- (4). following machine upgrade, there is a need to undertake PQC checks
- (5). following planned maintenance, there is a need to undertake PQC checks
- (6). interlocks are a major aspect which requires PQC, as they ensure the safety of the treatment delivery. Symmetry, uniformity and energy are examples of interlocks that are related to the performance of the beam and thus need to be checked in conjunction with performance measurements.

Therefore modern radiotherapy has reached a stage where the complexity of treatment delivery requires PSQC. The multiplicity of factors interacting is easily assessed by measurement of the overall outcome of the delivery, and it seems very unlikely that any PQC programme alone could provide the same level of confidence in complex treatment. Yet, following any intervention with the operation of the machine, prospective checks are essential to ensure adequate performance before returning it to clinical operation. In effect, both PQC and PSQC are essential. Both represent a resource burden, and a method to use them in a complementary manner could reduce that burden.

TARGETS AND COMPLIANCE IN QUALITY CONTROL

The addition of QC checks inevitably has an implication for manpower resources, availability of QC equipment and the

availability of treatment machines. A further consequence of increasing the amount of QC work is its likelihood of being carried out. With limited resource and access to equipment, it is reasonable to assume that the likelihood or probability (p_c) of completing an increasing amount of QC will diminish as the number of checks increases.

We can consider three options with regard to limited resource.

- (1). to limit the number of checks to a feasible number that will ensure they are completed
- (2). to have a large number of checks which are performed at random when resource is possible so that the probability of undertaking them all is the same but <1.0
- (3). to ensure a fixed number of checks which are considered essential are definitely undertaken and the rest performed if and when resource is available.

These three options are illustrated in the following example for a 20-item QC programme with only the resource to undertake 10 items. Figure 2 shows Option 1 in which only 10 items are always performed and the other 10 never carried out. It also indicates Option 2 with all 20 items being performed with a probability of 0.5.

Option 3 is shown such that Item 1 is always performed and so has a probability of 1.0. The variation in probability of undertaking the other items may have any profile as long as the area beneath the curve equates to 10 items. However, for this illustration, it is shown to decrease linearly across the entire 20 items.

The integrated total resource is 10 for all options. However, the distribution of the resource is spread differently across the 20 items reflecting different approaches.

The outcome in terms of implementation of the three options can be determined by combining Figures 1 and 2 on the basis that the reduction in PUMF from the introduction of an additional check will be the product of the reduction expected ideally and the probability that it will be carried out.

Figure 2. Variation of probability of a quality control item being performed for three methods of implementing a 20-item quality control programme with only resources for 10 items.

$$(p_{MA})_n = (p_{MA})_{n-1} - [(p_M)_{n-1} - (p_M)_n] \times (p_C)_n \quad (1)$$

where p_M is the ideal probability of undetected machine failure; p_{MA} is the actual probability of undetected machine failure; p_C is the probability of the QC check actually being performed; and n is the index for the n th QC check.

Although Equation (1) provides a mean which can be applied generally in order to determine an overall PUMF, it should be borne in mind that the actual relationship between a specific QC procedure and the reduction in PUMF is not explicitly known. The non-linear variation, Figure 1 is assumed in order to make a comparative examination of undertaking a QC programme with limited resource.

Combination of Figures 1 and 2 on this basis results in PUMF as listed in Table 1.

This indicates that to achieve the lowest PUMF, a set number of QC items equivalent to the resource available, Option 1 should always be undertaken. By contrast, performing all 20 items with lower probability of being completed as in Option 2 with a probability of 0.5 results in the highest PUMF. The option of ensuring a certain number is undertaken plus undertaking the others as and when possible, Option 3 results in a PUMF somewhere in between but closer to the lowest PUMF achievable. As the number of items which are guaranteed to be carried out is increased from 1 as in this example, the final PUMF will get closer to that obtained with Option 1.

In addition, ensuring performance of a set number and undertaking the others with a reduced probability is advantageous as deterioration in performance over a larger range of performance parameters is identified albeit over a longer range of time than the ideal. Also, the PUMF will be closer to the best achievable with the limited resource available.

This indicates that the Option 3 distribution model is preferred.

Using this distribution model for the probability of QC items being undertaken, it was possible to examine the effect of limited resource and the choice of a definite number of QC items to be carried out. Resource limits are considered with 14, 20 and 30 QC item programmes. The number of QC items definitely being carried out was varied from one as in Option 3 to eight items with the likelihood of the rest being carried out diminishing linearly to zero as in Option 3. This covered a range of total resource requirement from 14 to 30 in terms of QC items.

Figure 3 shows the resulting PUMF. It can be seen that the final value in each curve represents the ideal PUMF which can be obtained by undertaking all the QC items. Also shown in Figure 3 is the increasing resource which is required in order to achieve the number of guaranteed items.

From this model, the resource required and the minimum number of guaranteed items which must be carried out to achieve a particular PUMF can be determined. Table 2 presents these details for a PUMF of 0.428 which is the minimum which can be achieved with 14 QC items and for a PUMF of 0.289 which is the minimum that can be achieved with 20 QC items. Also tabulated is the efficiency required from the workforce undertaking the QC. This is the ratio of guaranteed items to the total resource.

This analysis shows that the PUMF achievable is dependent upon the QC programme, the number of guaranteed QC items which can be undertaken and the resource which is available. As mentioned above, the exact test, method, frequency and tolerances to ensure the ideal PUMF is achieved is unknown. Hence, even if the number of items in the QC programme was guaranteed to be carried out, the ideal would not be achieved. The parameter which best indicates the practical viability of the QC programme is the efficiency. The efficiency cannot be 100% either with respect to the QC items or from the practical nature of staff working, test equipment availability and treatment machine availability.

With an efficiency of 19%, Table 2 for 30 QC items indicates a poor use of resources which could be due to availability and organization or both. An aim of 70% seems a realistic target and certainly it should not fall <60%.

For the examples tabulated above, it can be seen that to achieve a PUMF of 0.428, the most effective use of resource is 20 QC items with about 10 guaranteed and requiring a resource of 14. Similarly, to achieve a PUMF of 0.289, 30 QC items are required with 15 guaranteed and with a resource of 21. The ratios are similar and suggest that for an efficient QC programme the following should apply:

$$\text{Guaranteed QC Items (G)} = 0.5 \times \text{Total QC items (T)} \quad (2)$$

$$\text{Resource Required (R)} = 0.67 \times \text{Resource for Total QC Items (T)} \quad (3)$$

These ratios enable G , T and R to be adjusted depending upon changes in the local situation. For example, if there is a reduction in staff or R , the value of T and G can be adjusted.

Table 1. Probability of undetected machine failure (PUMF) variation with options to undertake a 20-item quality control (QC) programme

Option	Description	PUMF
Ideal	All 20 QC items definitely carried out	0.289
1	10 QC items definitely carried out	0.556
2	Equal likelihood of all 20 items being carried out	0.644
3	Linear decrease in likelihood of being carried out	0.582

Figure 3. Variations in the probability of undetected machine failure (PUMF) and in required resource for three quality control programmes with increasing number of quality control items guaranteed to be performed.

SIGNIFICANCE OF VARIATION, TOLERANCES AND RESOURCE

The widely recognized tolerance of $\pm 3\%$ for overall treatment dose accuracy is attributable to clinical studies.^{20,21} This contributed to the recommended gamma index tolerance of $\pm 3\%/\pm 3\text{ mm}$ ²² and its subsequent wide use in PSQC. There are contemporary studies suggesting tighter tolerances²³ and individual

centres have occasion to use a tighter tolerance such as $\pm 2\%/\pm 2\text{ mm}$ for the head and neck.

The gamma index tolerance of say $\pm 3\%/\pm 3\text{ mm}$ encompasses all the variations in the treatment process, including all aspects from CT, treatment planning and beam modelling to treatment delivery. The worst case failure for a specific aspect of the machine performance would be that the overall treatment delivery as assessed by PSQC using a $\pm 3\%/\pm 3\text{ mm}$ gamma index criteria fell outside the tolerance because of a single fault which concerned that aspect. For example, the calibration of some MLC leaves. Although this is a theoretical upper limit, it sets a boundary and links tolerances between PQC and PSQC.

In reality, in order to track the performance of the machine, the tolerances used in PQC should reflect the performance which the machine can achieve and hence deviations from that will indicate and detect a variation in the machine, alerting the need for maintenance and/or adjustment to restore performance. These latter PQC tolerances are the ones which will provide confidence in the performance of the machine in routine use and that it is performing as per specification when accepted and following repair.

Therefore, although the above theoretical consideration of the desired variation for treatment provides an indication of a maximum tolerance boundary, the practical tolerance should reflect the performance of the machine and therefore track deviations in performance.

It is worth recalling that long-term measurement of a machine parameter will have a variation consisting of two components: the variance of the measuring system and the underlying variation of the machine. If a tolerance is too tight compared with the variation of the measurement, it will result in an excessive and unproductive number of investigative actions being required. For example, if the overall standard deviation of the measurement is $\sigma\%$ then the choice of a tolerance of $\pm\sigma\%$ will result, for normal operation of the machine, in 68% of measurements being within tolerance and 32% requiring some action to be taken. This would be an unacceptable amount of unproductive work. A tolerance of $\pm 2\sigma\%$ will result in almost 95% of measurements lying within tolerance and therefore only 5% will result in unproductive investigative work.

Table 2. Resource and efficiency variation for three quality control (QC) programmes and same probability of undetected machine failure (PUMF)

Total QC programme items	14	20	30	PUMF
Number of guaranteed items	14	9.7	3	0.428
Total resource needed	14	14.3	16	
Efficiency required, %	100.0	68.0	19.0	
Number of guaranteed items	–	20	13.5	0.289
Total resource needed	–	20	21.2	
Efficiency required, %	–	100.0	71.0	

In addition, there are three major aspects which impact on PSQC and therefore can be identified as the major items which should be assessed in routine PQC. These aspects are:

- mechanical and optical
- radiation field and
- absolute dose.

With regard to mechanical and optical, isocentre alignment, for example, will directly impact on the spatial tolerance of ± 3 mm and the distance meter will impact on the dose variation of $\pm 3\%$.

With regard to the radiation field, flatness and symmetry will impact on the $\pm 3\%$ dose variation while the position of the radiation field edge will impact on the ± 3 mm spatial tolerance.

Lastly, the absolute dose has no spatial impact; however, reproducibility will contribute to the overall dose delivery if the treatment is fractionated, and this is not an aspect assessed in PSQC.

When determining a working tolerance, the desired tolerance along with the variance of the measurement needs to be taken into account, and this is required to calculate the maximum tolerance boundary with regard to a single fault and a gamma index tolerance. In order to achieve $\pm 3\%$ with measurement equipment which has a variance of $\pm \sigma_m\%$, a working tolerance of $\pm(3 - 2\sigma_m)\%$ is required to ensure with 95% confidence that $\pm 3\%$ is being achieved.

Hence, for example, to ensure performance is within ± 3.0 mm when a measurement cannot be made to better than 0.5 mm, a worse case standard deviation for the measurement of 0.35 mm can be assumed. The working tolerance which will ensure that performance remains within ± 3.0 mm is $\pm(3.0 - 0.7)$ mm which is ± 2.3 mm. Likely a maximum tolerance boundary of ± 2.0 or ± 2.5 mm will be chosen.

The maximum tolerance boundary for the distance meter can be considered with respect to the ± 3.0 mm and $\pm 3.0\%$ as follows. To maintain the dose within $\pm 3\%$, the maximum tolerance boundary required is ± 15 mm at 1000 mm source-to-surface distance (SSD) and ± 12 mm at 800 mm SSD. However, if at best we can read the tip of a pointer to within ± 1 mm, then 2σ can be approximated to 1.4 mm as a worse case. Hence, the maximum tolerance boundary for the distance meter at 800 mm SSD would be ± 10 mm, which grossly exceeds the spatial tolerance of ± 3 mm. Therefore, taking into account the standard deviation of ± 0.7 mm for the measurement, working to a maximum tolerance boundary of $\pm(3.0 - 1.4)$ mm is required to ensure that the treatment is within ± 3 mm.

The lasers form the other critical aspect of spatial alignment and can usually be assessed to within ± 0.5 mm, giving a worse case estimate of $2\sigma = 0.7$ mm. This sets a maximum tolerance boundary of ± 2.3 mm.

Based upon practical experience, the performance of the distance meter and the lasers is better than these maximum tolerance boundary values.

Clearly, tolerances should be chosen, which strike a balance between monitoring the operation of the machine with a reasonable resource and ensuring that theoretically desirable targets are achieved. From a pragmatic point of view, choice of a tolerance based upon 5% unproductive investigation should have the priority. If this lies within the theoretical maximum tolerance boundary, it is excellent. However, if it does not, then it should still be used in preference to the theoretical maximum tolerance boundary owing to the fact that this reflects a limitation with the machine performance and that a high amount of unproductive work would be entailed without providing any benefit.

An additional refinement which enhances the detection of true deviations from normal operation is to set two tolerance bands. The first band is based upon the variance of the long-term measurement of a machine parameter and an unproductive investigation fraction of 5%, that is $\pm 2\sigma\%$. The second band lies between a 5% fraction and a 1% fraction of unproductive investigation, $\pm 3\sigma\%$. The likelihood of there being an actual problem should a measurement lie outside the $\pm 3\sigma\%$ level makes investigation essential. However, the interval between $\pm 2\sigma\%$ and $\pm 3\sigma\%$ provides room to delay investigation until it is clear that a number of consecutive measurements remain in that interval. The chance for three consecutive measurements to occur in that band for normal operation and no fault is vanishingly small. By contrast, if the actual value of the parameter has changed to be centred in this band, this will be established with 95% confidence from three consecutive measurements in the $\pm 2\sigma\%$ to $\pm 3\sigma\%$ band.

Practically, determining the initial standard deviation $\pm \sigma\%$ is not always a simple task. However, from several consecutive measurements, a best estimate should be initially determined and subsequent monitoring and investigation should enable this value to become established or altered as confidence grows through experience of the machine. Vigilance must be applied initially with the likelihood of undertaking investigations which are productive in establishing confidence in the tolerance rather than being productive corrective action.

Although these tolerances provide the means to monitor satisfactory operation of the machine, they should be considered with regard to the theoretical maximum tolerance boundaries based upon the targets for overall dose and positional delivery of the treatment.

Considering the major QC items mentioned above, Table 3 sets out theoretical maximum tolerance boundaries based upon a target of $\pm 3\%$ for dose and ± 3 mm for position and anticipated measurement uncertainty. Actual working tolerances based upon measurements should be less than these.

DAILY OUTPUT MEASUREMENT

A routine daily output measurement is worth discussion alone, as it provides a very simple yet substantial contribution to the confidence required for the use of the machine each day. As an integral part of the machine run-up process, it provides an immediate purpose: to measure the radiation dose the machine will provide. It provides the support staff with an opportunity in running the machine, to operate mechanical components such as filters, to control voltage and current supplies and to activate

Table 3. Theoretical maximum boundary tolerances for a single fault to compare with working tolerances obtained from measurement

Item	Description	Single-fault tolerance boundary	Measurement standard deviation	Theoretical maximum tolerance
1	Distance meter (mm)	± 3	± 0.7	± 1.6
2	Laser alignment (mm)	± 3	± 0.35	± 2.3
3	Symmetry, %	± 3	± 0.35	± 2.3
4	Uniformity, %	± 3	± 0.35	± 2.3
5	Radiation field edge alignment to indicator (mm)	± 3	± 0.35	± 2.3
6	Absolute dose, %	± 3	± 0.35	± 2.3
7	Dose reproducibility, %	± 3	± 0.35	± 2.3

electromechanical components and verify interlocks on attachments such as electron applicators. It taxes the cooling and vacuum system without the presence of the patient and the potential to interrupt treatment. It provides the assurance that the machine is running normally and will deliver the correct dose. In addition, with this occurring daily, the measurement of machine output can be considered as a guaranteed item in a routine PQC programme.

A RATIONALE TO COMBINE PATIENT-SPECIFIC WITH PROSPECTIVE QUALITY CONTROL

In order to ensure the most effective role for QC overall, a rationale is required between PSQC and PQC which maximizes the benefit from work and minimizes the resource required for it. It is clear that while PSQC is undertaken, the effectiveness of treatments is assured without knowledge of specific aspects of a machine's performance. By contrast, however, if a specific aspect of a machine has been altered or potentially changed, it is necessary to undertake PQC with regard to that aspect to ensure it has been restored to perform adequately. PSQC is too global in terms of the patient treatment to specifically provide assurance that the one-specific aspect has been correctly set. Likewise, it is not practically possible to ensure through PQC that the diverse range of treatments which will be delivered by conformal, intensity-modulated and adaptive radiotherapy will be accurately delivered.

PQC will continue to be essential for machines that do not provide treatments which require PSQC and for electron beams. However, for machines where routine PSQC is being undertaken, a rationale perspective is required which provides an appropriate balance between PSQC and PQC.

The EC Directive⁹ requirements for PQC are clear and essential. These apply to the following aspects:

- acceptance
- machine repair
- upgrades.

In addition to these, the following can be added:

- investigation of PSQC variation
- demonstration of safety interlock performance.

Routine PQC serves to demonstrate that the performance of the machine is adequate. However, PQC can be reduced when PSQC is being undertaken regularly. Flexibility can further reduce PQC as, for example, if PQC has been undertaken for machine repair or an upgrade, then any routine PQC could be cancelled. The resource requirement for a particular PQC check and the combination of PQC checks are further aspects which will reduce resource. For example, an output measurement typically relies on the use of the distance meter or the lasers to position the measurement device. Hence, a simple measurement of machine output encompasses the two checks with the chance of a double fault less likely than a single.

In order to assess the impact on PQC of taking a combined approach, a typical PQC programme is outlined in Table 4. Two situations are presented: PQC only and PQC in conjunction with PSQC. Approximate times based upon typical QC experience are given in order to evaluate the impact on resource.

It is reasonable to consider the programme and requirements totalled over 1 year and to identify QC checks which it would be desirable to guarantee and those which it would be acceptable to undertake with less regularity in line with the model identified previously.

With the introduction of PSQC, it is further reasonable to expect that for normal patient throughput, PSQC will be undertaken at least weekly, and hence, for a machine upon which only PQC was being undertaken, the major items should be undertaken weekly. The programmes include the major items identified in Section 5 with regard to the PSQC tolerances of $\pm 3\%$ and ± 3 mm. Machine output measurement is already included as a guaranteed item because of its measurement at daily run up. Dose reproducibility could also be removed by inclusion of it in the daily run-up output measurement on occasions.

The programme can be considered to have an overall total of 20 items with inclusion of the daily output measurement. This is roughly in line with the model above, Equation (2). The resource required can be identified in man-hours by estimating the total time for all the items and applying Equation (3).

Table 4. An example prospective quality control programme for megavoltage photons with and without patient-specific quality control (PSQC)

Item	Description	Time (min)		Frequency	
				No PSQC	With PSQC
1	Output measurement	30		Daily	Daily
2	Distance meter	10			
3	Laser alignment	10			
4	Flatness and symmetry, $G = 0$	40	Guarantee	Weekly	Monthly
5	Radiation field edge position	60			
6	Field position reproducibility	15			
7	Treatment front pointer	10			
8	Energy safety limits	30			
9	Flatness/uniformity safety limits	30	Guarantee	Monthly	Monthly
10	Backup dose channel/timer	20			
11	Flatness and symmetry, $G = 90$	40			
12	Flatness and symmetry, $G = 180$	40			
13	Flatness and symmetry, $G = 270$	40			
14	Energy	15			
15	Dose linearity	30			
16	Mechanical isocentre	20	Additional	Monthly	Monthly
17	Radiation isocentre	60			
18	Gantry scale zero	20			
19	Diaphragm scale zero	20			
20	PSS scale zero	20			
		Yearly	Total (min)	12,440	6620

PSS, patient support system.

A reasonable estimate of time is 12,440 min per year which would require a resource of 8334 min per year or 11.6 man-hours per month.

For a machine on which PSQC is being routinely performed on a weekly basis, the number of items remains the same although the frequency and hence the resource for PQC is reduced considerably. The resource required based upon Table 4 would be 4435 min per year or about 6.2 man-hours per month. Estimates for the PQC for photons with and without PSQC show that the resource can be almost halved.

The QC programme for electron beams remain prospective and unaffected by PSQC.

CONCLUSION

QC remains an essential part of radiotherapy treatment and the complexity of modern treatment delivery has made PSQC the most effective means to ensure safe treatment delivery. Although PQC continues to have a significant role, it no longer solely provides comprehensive assurance of treatment delivery. All QC has resource implications and continually increasing this requirement is not cost effective. The implementation of PSQC needs to be

balanced with a reduction in PQC. The overall gamma index tolerances chosen for PSQC provide theoretical maximum tolerance values based upon a single fault for aspects of PQC against which practical tolerances can be compared.

The continual increase in the number of PQC checks is not a cost-effective use of resource because of the likely non-linear variation in the PUMF. The most effective PQC scheme is to identify a subset of guaranteed checks with the additional checks being performed on a random basis when resource and opportunity arises. The number of guaranteed checks should be about half the total number of QC checks required, and the resource required for this will be about 67% of the resource which would be required to undertake all the checks. This allows a margin for unforeseen problems such as machine or equipment availability and ensures that staff will work with a high efficiency and on this basis be cost effective.

A rational scheme for PQC with and without PSQC has been presented which identifies an overall set of QC checks to be undertaken on the basis of guaranteed checks and additional checks. PSQC is now unavoidable owing to the complexity of modern radiotherapy delivery, and although PQC remains

essential for specific instances such as machine repair, the two need to be used in conjunction to maximize benefit and minimize resources. Local workload for PSQC will depend as to whether it is on a class basis such as sampling 1 prostate treatment in 10 or on an individual patient basis; checking every patient or patients with a specific concern. The local system can, however, be customized in order to ensure that, for example, every machine accommodates a PSQC at least once weekly with a complementary reduction in PQC.

These schemes can be used locally to determine the resource required in man-hours and the examples chosen demonstrated that with PSQC which is now unavoidable, the amount of PQC can be halved.

Tests vary in taking different lengths of time and there being different failure rates for the item being checked. These would be aspects significant for the determination of resource and the

choice of guaranteed items. It may be possible, concerning the latter aspect to identify tests which are more or less necessary than others in terms of the probability of failure. This aspect has not been addressed in this article and may well be influenced by local factors and specific machine experience.

Further reductions in PQC is also achievable by avoiding routine PQC, when it has been undertaken for breakdown and repairs etc. However, such flexibility may not be possible owing to the constraints of patient and staff scheduling.

This review attempts to provide a rationale which balances PQC with PSQC with a view to reducing the resource required and to use that resource cost effectively. It provides a framework to guide the work of physicists and technicians in their role of assuring satisfactory treatment with regard to the QC programme, the tolerances used and the resource required.

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