PHYSICS CONTRIBUTION

PERFORMANCE OF DIFFERENT RADIOTHERAPY WORKLOAD MODELS


*Radiation Oncology Research Unit, Division of Cancer Care and Epidemiology, Queen’s University Cancer Research Institute, and Kingston Regional Cancer Centre, Kingston General Hospital, Kingston, Ontario, Canada; † Department of Radiation Oncology, Cancer Therapy Centre, Liverpool Hospital, Liverpool BC, NSW, Australia

Purpose: The purpose of this study was to evaluate the performance of different radiotherapy workload models using a prospectively collected dataset of patient and treatment information from a single center.

Methods and Materials: Information about all individual radiotherapy treatments was collected for 2 weeks from the three linear accelerators (linacs) in our department. This information included diagnosis code, treatment site, treatment unit, treatment time, fields per fraction, technique, beam type, blocks, wedges, junctions, port films, and Eastern Cooperative Oncology Group (ECOG) performance status. We evaluated the accuracy and precision of the original and revised basic treatment equivalent (BTE) model, the simple and complex Addenbrooke models, the equivalent simple treatment visit (ESTV) model, fields per hour, and two local standards of workload measurement.

Results: Data were collected for 2 weeks in June 2001. During this time, 151 patients were treated with 857 fractions. The revised BTE model performed better than the other models with a mean observed–predicted of 2.62 (2.44–2.80). It estimated 88.0% of treatment times within 5 min, which is similar to the previously reported accuracy of the model.

Conclusion: The revised BTE model had similar accuracy and precision for data collected in our center as it did for the original dataset and performed the best of the models assessed. This model would have uses for patient scheduling, and describing workloads and case complexity. © 2003 Elsevier Science Inc.

INTRODUCTION

In any radiotherapy department, there is a need to balance the quantity of services provided against the quality of services provided. Health care administrators, be they public or private, want to deliver the largest volume of services possible in the most efficient way. Therapists, on the other hand, struggle with the pressure of increasingly complicated treatment plans and large volumes of patients requiring treatment. This can threaten the quality of services delivered (1). Disturbance of the balance may lead to poor morale, critical errors in treatment delivery, or an inefficient, expensive department. These factors are the main reason investigators have undertaken studies of radiotherapy workload and complexity. The specialty has turned to the rational arbiter of science to define fair expectations. In this way, all health care providers should feel that they are achieving optimal efficiency with a manageable workload.

There have been two studies done using similar methodology where patient- and treatment-related information was collected prospectively and used to construct a multivariate model that predicts treatment time (2, 3). Delaney et al. in Australia have developed a new measure of linear accelerator (linac) workload called a basic treatment equivalent (BTE). In this model, 1 BTE unit is the work it takes to treat a simple 1- or 2-field treatment with up to two shielding blocks. Higher BTE units represent more complicated treatments. One BTE unit takes approximately 10 min to treat. Burnet et al. in the U.K. have used similar methodology to develop their own model.

However, most cancer centers or treatment providers have their own internal workload standards, which may or may not be based on measurements. In other cases, professional associations have set standards that are adopted by individual providers (4).

The purpose of this study was to assess the fit of different linac workload models developed elsewhere, as well as the standards used locally, with patient and treatment data collected prospectively in our own center.

Reprint requests to: Dr. William J. Mackillop, Division of Cancer Care and Epidemiology, Queen’s University Cancer Research Institute, Kingston General Hospital, 76 Stuart Street, Kingston, Ontario K7L 2V7 Canada. Tel: (613) 548-6149; Fax: (613) 548-6150; E-mail: william.mackillop@krcc.on.ca

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METHODS AND MATERIALS

The Center

Kingston Regional Cancer Center is one of nine regionalized cancer centers in the province of Ontario, Canada. The radiation oncology department has eight radiation oncologists and a new patient referral rate of about 1800 cases per year. All major tumor sites are treated, except for pediatrics. There are three linear accelerators: one 4-MV, and two dual-energy 6/15-MV linear accelerators with electron capabilities within a range of energies. The dose rate for these linear accelerators ranges between 250 and 300 MU per minute with a calibration factor of 1 MU/cGy. All linear accelerators use standard lead or poured blocks. Multileaf collimators were not in use during the time of the study. Special techniques such as stereotactic radiosurgery, total body irradiation, or total skin electrons are not performed at our center.

The radiation therapists work in pairs, with overlapping shifts. In the early morning and late afternoon, machines are staffed with two pairs. There are approximately 36 15-min treatment time slots available in a day, although some patients are booked for 20 or 30 min instead of 15.

Data collection

Data were collected for every fraction delivered during a 2-week period. Data collected for each fraction included diagnosis, treatment unit, treatment intent, treatment technique, treatment site, beam type, fraction number, patient age, Eastern Cooperative Oncology Group (ECOG) performance status, special treatment requirements (e.g., general anesthesia), number of fields, number of wedges, total number of shielding blocks per treatment, number of junctions, and port films. A dedicated research radiation therapist collected and entered all data on a daily basis during the study. Fraction duration was defined as the time when the patient entered the room until the time the patient left the room. The radiation therapists used a stopwatch to time the duration of every treatment fraction.

Data quality

The data collection form, stopwatch performance, and electronic data entry form were piloted over one day on all of the treatment machines. Radiation therapists were asked to complete a questionnaire regarding the process, data collection sheet, and stopwatch performance. Feedback was shared to refine the process and to minimize missing data.

Completed data collection forms were compared with the final paper and electronic schedules as well as the record and verify system output for each treatment machine. Patients treated who were added to the initial schedule for each day were verified and captured. Machine on and off times were obtained from the record and verify output and verified with analog wall clocks. The radiation therapist escorting the patient into the room and out of the room carried the stopwatch for continuity.

On completion of the data entry for all treatment machines, the database variables were subjected to missing, logical, and frequency checks. All identified deficiencies were corrected, and the database was rechecked to verify the completeness and accuracy of the data.

Methods to compare models

Each measure we assessed could be converted to a predicted treatment time. We therefore assessed the performance of the various predictive models by comparing the predicted treatment time with the actual treatment time for every fraction. We report the percentage of fractions in which the absolute residual (observed time – expected time) lay within 2 and 5 min, and the number of minutes within which 80% and 95% of the residual discrepancies lay. We also calculated the mean of the absolute value of the residuals, along with the 95% confidence limits. The closer the mean is to zero the better the performance of the model.

Models evaluated

Equivalent simple treatment visit (ESTV). The Inter-Society Council for Radiation Oncology is an American organization that has published standards for radiotherapy (4). This reference is known as the “blue book” and was last updated in 1991. Treatments are divided into three categories. A simple treatment is a 1- or 2-field parallel-opposed pair with simple shielding. An intermediate treatment is using more than two fields, having more than one treatment site, or more than two blocks. A complex treatment is having three or more treatment sites, or tangents with wedges. A simple treatment is equivalent to 1 ESTV unit and takes approximately 15 min to treat. The more complicated treatments are worth more ESTV units.

Basic treatment equivalent (BTE). The information collected was used to calculate the BTE for each patient using the refined BTE equation (3). This equation estimates the time required to deliver a fraction of treatment as follows:

\[
R = F (4.2 + 1.8B1 + 5.7B2 + 1.2J + 1.3N + 1.1S + 0.5W + 1.5P + 2.0E + 6.6A)
\]  

(1)

where \(F = 1.5\) for the first fraction and \(1\) for all subsequent fractions; \(B1 =\) photon beam; \(B2 =\) mixed photon/electron beam; \(J =\) junction; \(N =\) number of fields; \(S =\) number of shielding blocks; \(W =\) number of wedges; \(P =\) number of port films or electronic portal imaging exposures; \(E = 1\) if performance status is ECOG > 2 (otherwise \(E = 0\)); \(A = 1\) if use of sedation or anesthesia is required (otherwise \(A = 0\)); and \(R =\) predicted treatment time in minutes. To calculated the BTE, it is assumed that 1 BTE is approximately equal to a basic treatment of 10 min, or \(BTE = R/10\). Unlike treatment time alone, BTE provides a way of assessing complexity of workload.

Addenbrooke simple and complex models. The information collected was also used in the simple and complex
The model reported from Addenbrooke (2). In this case, the simple model was calculated as follows:

\[
R = 4.99 + 2.68F + 1.94N + 0.53S + 0.55E + 8.6A + 1.99B + 0.74D \quad (2)
\]

where F = 1 for first fraction otherwise 0; N = number of fields; S = number of shielding blocks; E = ECOG performance status score; A = 1 for use of anesthesia otherwise 0; B = number of beam films; d = number of diodes; and R = predicted time in minutes.

The complex model was:

\[
R = 0.17 + 2.72F + 2.31N + 0.38S + 0.74E + 8.58A + 2.11B + 0.80D + 'site/technique constant' \quad (3)
\]

The variables are as above. The reader is referred to the original publication for the site/technique constants (2).

**Fields per time.** Another standard commonly used is fields per time. We evaluated this measure by using 5 min per field for the predicted time.

**Ontario standards.** The Kingston Regional Cancer Center is part of a larger provincial cancer care body, Cancer Care Ontario (CCO). CCO has set standards for linac throughput based on center size. In our center, it is expected that a linac can treat 3.7 patients per hour, or 16.2 min per patient.

The time interval we measured was from when the patient walked into the room to when the patient walked out of the room. The CCO standard includes this time and the time between delivering each fraction. We therefore used our observations and the total amount of time the machine was on to create a conversion ratio to account for the extra time between patients. The correction factor yielded an average treatment duration of 12.4 min, which we compared with the actual treatment times (fraction time incorporating time in between fractions = stopwatch time * 1.3).

The National Hospital Productivity Improvement Program (NHPIP) was initiated in Canada in 1989 (5). Its purpose was to provide a nationally uniform basis for measuring workload and human resources output. Data on radiotherapy workload is collected in real time by therapists as part of this program. Each activity associated with treatment planning or delivery has an assigned code, and each code is worth a certain number of units. Each unit is worth 1 min of time. For example, there are treatment codes for delivering a 2-field fraction, 3-field fraction, etc. There are also codes for performing port films or patient instruction. The model was originally generated by defining a list of all possible activities related to treatment (and planning) and determining the average time it took for each of the activities. The average time was based on observational studies performed at centers across the nation. In Ontario, the NHPIP data are stored in the provincial electronic clinical database, the Oncology Patient Information System (OPIS). It contains diagnostic, therapeutic, and follow-up information on all patients registered at a regional cancer center (6). We captured all of the NHPIP treatment-related activity codes from OPIS for the treatments delivered during the time of the study and compared the expected time based on the data coded and the observed time for each fraction.

### RESULTS

**Collected data**

We collected data for 2 weeks (10 working days) in June 2001. During this time, 151 patients were treated with 876 fractions of radiotherapy (RT). Nineteen fractions had no treatment time recorded, leaving 857 fractions for analysis. The mean fraction time was 13.7 min (95% CI 13.3–14.0). The median fraction time was 12.5 min. Treatment unit A had one scheduled down day during the 2 weeks.

Tables 1–4 describe the type of work occurring on each of the treatment units, in addition to the center as a whole. Treatment unit B delivered more 4-field treatments, and unit C delivered more 2-field treatments (Table 2). Unit B delivered a large proportion of the pelvis treatments. Unit C delivered a majority of the head-and-neck and breast treatments (Table 3). Unit C delivered substantially more palliative treatments and had more first treatments (Table 4).
Table 5 describes the amount of time each unit spent working each day. Each machine was on for about the same time every day. Each unit appears to finish the day with about 30 min to spare. However, this time is usually used for completing administrative tasks or treating emergency patients added on that day. Unit C was not completely booked during the time of the study. This is reflected in the lower on time and higher between fraction time. The average amount of time between fractions is similar to what has been reported by Delaney (3).

Assessment of different models

Before calculating the BTE formula, we determined how long it took to treat simple treatments at our center. Figure 1 is a histogram of all the fraction times for 1- or 2-field treatments with one or two shields and good performance status patients. The mean is 11.4 (95% CI 10.7, 12.2), and the median is 10.9. In a previous Canadian study, 15 min was chosen as a single unit of time (7). Based on these results, we felt 10 min was a better approximation of the time required for a simple treatment.

The accuracy and precision of each model is reported in Table 6. The revised BTE model predicted 50% of treatment times within 2 min and 88% of treatment times within 5 min. Eighty percent of observations were predicted within 4 min, and 95% of observations were predicted within 7 min. The corresponding values from the Australian study of the revised BTE are similar, with 87% of treatment times within 5 min and 95% of the observations within 7 min (3).

Results of the same type of analysis using the original BTE equation, the simple and complex models reported from the U.K., and the CCO standard indicate that these models perform similarly and not as well as the modified BTE model. The 5 min per field estimate and the NHPIP estimate performed worse than these.

For the ESTV model, we used 10 min as the time to treat one ESTV, which is similar to 1 BTE, in addition to the 15 min called for by the original description of the model. This improved the performance of the model but did not make it any better than the revised BTE model. We also categorized all treatment fractions as simple, intermediate, or complex based on ESTV definitions. Using this categorization, we found that the intermediate treatment category took the longest to treat (median 14.0 min), followed by the complex category (12.3 min) and then the simple category (11.0 min). These times were all statistically different in pairwise comparisons (p < 0.0001).

The model with the lowest mean absolute difference was the revised BTE model. The model with the highest mean absolute difference was the ESTV model (15 min). The confidence limit around the mean absolute difference of the revised BTE model excludes the values of the next best model (Addenbrooke simple), meaning its performance is statistically better.

Figure 2 is a plot of the actual treatment time vs. the residual of the actual – predicted time, using the BTE model. This plot indicates that the BTE model was more likely to systematically underestimate treatment time for longer treatments than to overestimate treatment times for shorter treatments. We also evaluated the residuals first vs. subsequent fraction but did not find systematic differences (not shown).

Table 2. Description of fields per fraction by unit

<table>
<thead>
<tr>
<th>Treatment unit (no. fractions)</th>
<th>1 field</th>
<th>2 fields</th>
<th>3 fields</th>
<th>4 fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (285)</td>
<td>32 (48%)</td>
<td>146 (36%)</td>
<td>40 (24%)</td>
<td>67 (30%)</td>
</tr>
<tr>
<td>B (325)</td>
<td>21 (31%)</td>
<td>95 (24%)</td>
<td>67 (40%)</td>
<td>142 (63%)</td>
</tr>
<tr>
<td>C (247)</td>
<td>14 (21%)</td>
<td>158 (40%)</td>
<td>60 (36%)</td>
<td>15 (7%)</td>
</tr>
<tr>
<td>Whole center (857)</td>
<td>67</td>
<td>399</td>
<td>167</td>
<td>224</td>
</tr>
</tbody>
</table>

Table 3. Description of sites treated by each treatment unit

<table>
<thead>
<tr>
<th>Treatment unit (no. fractions)</th>
<th>Breast</th>
<th>H&amp;N</th>
<th>Pelvis</th>
<th>Chest</th>
<th>Brain</th>
<th>Limb</th>
<th>Abdomen</th>
<th>Bone</th>
<th>2 sites</th>
<th>3 sites</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (285)</td>
<td>52 (30%)</td>
<td>0</td>
<td>94 (36%)</td>
<td>75 (56%)</td>
<td>17 (29%)</td>
<td>3</td>
<td>12 (21%)</td>
<td>4</td>
<td>5</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td>B (325)</td>
<td>26 (15%)</td>
<td>22</td>
<td>147 (36%)</td>
<td>47 (35%)</td>
<td>0</td>
<td>0</td>
<td>43 (21%)</td>
<td>4</td>
<td>11</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>C (247)</td>
<td>96 (55%)</td>
<td>52</td>
<td>21 (70%)</td>
<td>12 (8%)</td>
<td>41</td>
<td>11</td>
<td>1 (77%)</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Whole center (857)</td>
<td>174</td>
<td>74</td>
<td>262</td>
<td>134</td>
<td>58</td>
<td>14</td>
<td>56</td>
<td>12</td>
<td>25</td>
<td>10</td>
<td>38</td>
</tr>
</tbody>
</table>
We have assessed the ability of a number of different models to predict radiotherapy treatment times using a prospective set of patient and treatment data collected at our center. The refined BTE model had the best fit, with accuracy and precision values in Kingston, Canada similar to those reported in the original Australian study. The original BTE and Addenbrooke models did not fit as well. The likely explanation is because they were based on data from a single center. Both the BTE and Addenbrooke models were generated by multivariate regression with weights assigned for each variable. These weighting factors may be too specific for the center that created the model and make the model difficult to apply to other centers. The refined BTE model was based on data from 36 different centers in two different countries. This makes it more likely to be generalizable to other centers.

The inconsistency of ESTV times has been previously reported (8, 9) with results similar to ours. Other studies have also questioned the validity of the ESTV model, suggesting that it underestimates the number of patients that can be serviced by a single machine (10). Perez et al. (9) have stressed that every center should perform their own time–motion study before applying the “blue book” recommendations. These inconsistencies and conclusions may partly be due to the fact that the “blue book” is a product of expert opinion, not experimental or observational study.

To our knowledge, evaluation of the CCO or NHPIP standards has not been published previously. Unlike Australia, where the standard productivity measure in use is fields per hour, in Ontario the standard is patients (or fractions) per hour. At best, this value is a rough guide for assessing workload and is lacking when it comes to issues like patient booking or workload evaluation of different treatment units or centers. It does not account for any range in treatment complexity that might impact on treatment times or throughput. It is this feature of the BTE model that is its strength.

The NHPIP codes potentially allowed for an improved ability to predict treatment time because of numerous codes

**DISCUSSION**

<table>
<thead>
<tr>
<th>Treatment unit</th>
<th>Total number patients</th>
<th>Number of first fractions (%)</th>
<th>Number of subsequent fractions (%)</th>
<th>Number of curative fractions (%)</th>
<th>Number of palliative fractions (%)</th>
<th>Average number of fractions/day</th>
<th>Total BTE over study</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>52</td>
<td>27 (32)</td>
<td>258 (33)</td>
<td>260 (39)</td>
<td>25 (13)</td>
<td>31.7</td>
<td>352.4</td>
</tr>
<tr>
<td>B</td>
<td>51</td>
<td>25 (30)</td>
<td>300 (39)</td>
<td>261 (39)</td>
<td>64 (35)</td>
<td>32.5</td>
<td>427.6</td>
</tr>
<tr>
<td>C</td>
<td>56</td>
<td>32 (38)</td>
<td>215 (28)</td>
<td>152 (22)</td>
<td>95 (52)</td>
<td>24.7</td>
<td>312.2</td>
</tr>
<tr>
<td>Whole center</td>
<td>151*</td>
<td>84</td>
<td>773</td>
<td>673</td>
<td>184</td>
<td>29.6</td>
<td>1092.2</td>
</tr>
</tbody>
</table>

BTE = basic treatment equivalent.

* Eight patients were treated on more than one unit.

<table>
<thead>
<tr>
<th>Treatment unit</th>
<th>Potential operational time (h/d) [1]</th>
<th>Operational time (h/d) [2]</th>
<th>On time (h/d) [3]</th>
<th>Unused potential operational time (h/d) [4]</th>
<th>Sum of time between fractions (h/d) [5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>9.8</td>
<td>9.2</td>
<td>6.9</td>
<td>0.6</td>
<td>2.3</td>
</tr>
<tr>
<td>B</td>
<td>9.8</td>
<td>9.1</td>
<td>7.1</td>
<td>0.6</td>
<td>2.0</td>
</tr>
<tr>
<td>C</td>
<td>9.8</td>
<td>9.2</td>
<td>6.3</td>
<td>0.5</td>
<td>2.9</td>
</tr>
</tbody>
</table>


Table 4. Description of work occurring on each unit over the study period

Table 5. Description of treatment time on each unit
for different activities. However, this did not bear out in our evaluation. The model’s performance may be due to poor data quality or a poor model. Because there is no audit process and most therapists do not understand the system, it is quite possible that the data quality in this database is suspect. The performance of the NHPIP codes raises doubt about the utility of this information for any purpose and raises the question of whether it is worthwhile spending the time to collect the information using this system.

The BTE model in its present form does not account for newer technologies, such as electronic portal imaging, dynamic wedges, or multileaf collimation (MLC). The Addenbrooke group has demonstrated the impact of new techniques on patient throughput, using 3D conformal treatment for prostate cancer as an example. This paper also estimated the impact of MLC, or automated machine setup, by combining other published data on improved treatment efficiency with their own BTE model. Updated versions of the BTE model could be created to deal with these factors.

The BTE model’s strength is as a measure of throughput. It does not account for many of the factors that contribute to the cost of delivering treatment, such as quality assurance, data entry, research, or unforeseen delays. In addition, it does not account for other activities that are part of a cancer clinic such as consultations, planning, simulation, counseling, and teaching. In the United States, Medicare reimbursements are based on a Resource-Based Relative Value Scale. In this system, physician payment is determined by the

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**Table 6. Difference between observed and predicted times**

<table>
<thead>
<tr>
<th>Model</th>
<th>1% within</th>
<th></th>
<th>Observed – predicted</th>
<th>for</th>
<th>Mean of absolute differences</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>±2 min</td>
<td>±5 min</td>
<td>80% of obs</td>
<td>95% of obs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revised BTE model</td>
<td>50.1</td>
<td>88.0</td>
<td>3.98</td>
<td>7.07</td>
<td>2.62</td>
<td>2.44–2.80</td>
</tr>
<tr>
<td>Original BTE model</td>
<td>36.2</td>
<td>80.8</td>
<td>4.95</td>
<td>8.22</td>
<td>3.34</td>
<td>3.14–3.55</td>
</tr>
<tr>
<td>5 min per field</td>
<td>30.6</td>
<td>64.5</td>
<td>7.02</td>
<td>10.2</td>
<td>4.35</td>
<td>4.09–4.61</td>
</tr>
<tr>
<td>Addenbrooke simple</td>
<td>43.1</td>
<td>83.3</td>
<td>4.43</td>
<td>8.95</td>
<td>3.09</td>
<td>2.88–3.30</td>
</tr>
<tr>
<td>Addenbrooke complex</td>
<td>44.9</td>
<td>79.0</td>
<td>5.14</td>
<td>10.33</td>
<td>3.36</td>
<td>3.12–3.60</td>
</tr>
<tr>
<td>ESTV (10 min)</td>
<td>45.9</td>
<td>79.5</td>
<td>5.13</td>
<td>11.3</td>
<td>3.50</td>
<td>3.22–3.78</td>
</tr>
<tr>
<td>ESTV (15 min)</td>
<td>14.1</td>
<td>48.2</td>
<td>7.78</td>
<td>9.95</td>
<td>5.38</td>
<td>5.15–5.60</td>
</tr>
<tr>
<td>Ontario (12.4 min/fr)</td>
<td>43.0</td>
<td>78.5</td>
<td>5.13</td>
<td>10.73</td>
<td>3.49</td>
<td>3.23–3.75</td>
</tr>
<tr>
<td>NHPIP codes</td>
<td>29.7</td>
<td>60.5</td>
<td>7.38</td>
<td>12.42</td>
<td>4.89</td>
<td>4.57–5.22</td>
</tr>
</tbody>
</table>

*Abbreviations:* obs = observation; fr = fraction.

Details shown are the percentage of treatments whose predicted times fall within 2 and 5 min of those observed, and the minutes difference between observed and predicted times for 80% and 95% of the observations.
resource costs needed to provide a service. The cost of a service is divided into three components: physician work, practice expense, and professional liability insurance. The practice expense component is based on the applicable Current Procedural Terminology (CPT) codes. The BTE model could provide an alternative method of describing the work (and hence resources) required to deliver treatment, e.g., cost/BTE.

The highly technical nature of radiotherapy predisposes it to measurement. The desire of all health care providers to have optimal efficiency must be balanced against the need for therapists to have the time to avoid mistakes and to be flexible when dealing with ill patients. A model that was accepted by both parties would be a step forward in trying to allocate human and capital resources and could potentially become part of a larger management strategy. If similar results were found at other Ontario centers, it might be possible to build consensus around what information is most important to collect and how it could be used.

REFERENCES