Accelerating the future: designing a robust and affordable radiation therapy treatment system for challenging environments

Manjit Dosanjh, CERN and JAI-Oxford (on behalf of STELLA collaboration)
Cancer is a growing global challenge

- Globally, 19.3 million new cases per year diagnosed and 10 million deaths in 2020
- This will increase to 27.5 million new cases per year and 16.3 million deaths by 2040
- 70% of these deaths will occur in low- and middle-income countries (LMICs)
- 9 out of 10 deaths for cervical cancer and 7 out of 10 breast cancer are in LMICs

Radiation therapy is a key tool for treatment for around 60% patients
DNA damage is induced via single and double DNA strand breaks, DNA cross-linking.

Aims of Radiotherapy:
• Irradiate tumour with sufficient dose to stop cancer growth
• Avoid complications and minimise damage to surrounding tissue

Current radiotherapy methods:
• 5 - 25 MV photons
• 5 - 25 MeV electrons
• 50 - 400 MeV/u hadrons

![Graph showing the relative dose per depth for different particle types: Electrons (21 MeV), Carbon (270 MeV/u), Photons, and Protons.](Manjit Dosanjh, CERN-IPAC 27.06.2022)
Key external radiation therapy delivery systems

- Cobalt 60 machines
- **Linear accelerators (LINACs)**
  - Image-guided radiotherapy (IGRT); MR-guided etc.
  - Particle therapy (proton and carbon).....new ideas presented here
    - Compact Accelerators: SLAC and Peking University talks
    - Compact synchrotron Helium (Vretener talk)
- VHEE – compact electron machine for deeper penetration
- FLASH therapy could be possible for all particles ---more patients
For nearly 60% of cancers, RT is most useful tool for cancer cure or pain-relief; inadequate supply of RT linear accelerators (LINACs).

- Gap greatest in low-middle income countries (LMICs)
- 70% of the cancer deaths will occur in LMICs
  - 9 out of 10 deaths for cervical cancer and 7 out of 10 breast cancer are in LMICs
- Only 10% of patients in LMIC have access RT
- Current LINAC technology is complex, labor intensive, and high cost to acquire, install, operate and service.¹

Radiation Therapy is an essential part of cancer treatment. However only 10% of patients in low-income regions have access.
Great strides have been made in the fight against cancer

However, there are dramatic disparities in Access

<table>
<thead>
<tr>
<th>Country</th>
<th>LINACs</th>
<th>Population</th>
<th>People per LINAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethiopia</td>
<td>1</td>
<td>115 M</td>
<td>115,000,000</td>
</tr>
<tr>
<td>Nigeria</td>
<td>7</td>
<td>206 M</td>
<td>29,000,000</td>
</tr>
<tr>
<td>Tanzania</td>
<td>5</td>
<td>59.7 M</td>
<td>11,900,000</td>
</tr>
<tr>
<td>Kenya</td>
<td>11</td>
<td>53.9 M</td>
<td>4,890,000</td>
</tr>
<tr>
<td>Morocco</td>
<td>42</td>
<td>36.9 M</td>
<td>880,000</td>
</tr>
<tr>
<td>South Africa</td>
<td>97</td>
<td>59 M</td>
<td>608,000</td>
</tr>
<tr>
<td>UK</td>
<td>357</td>
<td>67 M</td>
<td>187,000</td>
</tr>
<tr>
<td>Switzerland</td>
<td>83</td>
<td>8.6 M</td>
<td>103,000</td>
</tr>
<tr>
<td>US</td>
<td>3727</td>
<td>331 M</td>
<td>88,000</td>
</tr>
</tbody>
</table>

Examples of Disparity

**Africa**: 400 RT-LINACs for > 1 billion people needs around 4000

**US**: Around 4000 LINAC for 330 Million people

**Ethiopia**: 115 Million people – 1 LINAC

Nigeria 7 machines for 220 million people only a couple of trained linear accelerator maintenance engineers, has 85 radiation and clinical oncologists and Abuja is the only place that has Medical Physics Dept.

Manjit Dosanjh CERN- IPAC 27.06.2022
GNP and Ratio of Inhabitants to Linacs and Cancer Mortality

Manjit Dosanjh, CERN-IPAC, 27.06.2022
Shortage and challenge is not only in Africa


Radiation therapy capacities in Europe

SEEIIST Initiative

South-East European International Institute for Sustainable Technologies
- Diagnostic and radiotherapy capacity;
- Cancer statistics;
- Human capacity, education and potential in research related areas;

**Questionnaire for Oncologists**

**Questionnaire for Scientists**

**Questionnaire for Regulators**
Linacs and Cancer Mortality in SEE Region (Balkan Peninsula)
Current status of RT

• Current Linacs provide very good treatment both in terms of technical capability and throughput.

• However current LINAC technology is complex, labour intensive, and expensive to acquire, install, operate and service in both LMICs and HICs.\(^1\)

• Linac technology requires strong, robust and reliable infrastructure (power, clean water, supply chain etc.) to operate

• Many Linacs are purchased or deployed in Africa and LMICs without sufficient training. Many are never used or not close to their capacity

• LINAC servicing can be slow and very expensive. Service contracts are expensive and not always purchased. Long down times (months or more).

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Project STELLA: Smart Technologies to Extend Lives with Linear Accelerators

Project STELLA is a unique global collaboration involving some of the best physics and medical talent, expertise from leading laboratories in accelerator design and, importantly, input and collaboration from users in Africa, other LMICs and HICs.

The goal of this project is to enable cancer care through innovative technology that is disruptive and is centred in mentoring.

STELLA needs to be:

• Robust, modular, reliable and easier to use machine
• Affordable with the aim to expand access to RT global
1st workshop on:
“Design Characteristics of a Novel Linear Accelerator for Challenging Environments”

Norman Coleman (ICEC) David Pistenmaa (ICEC) Manjit Dosanjh (CERN)

http://indico.cern.ch/event/560969/

International Atomic Energy Agency (IAEA)
James Martin Center for Nonproliferation Studies (CNS)
National Aeronautics and Space Administration (NASA)
National Nuclear Security Administration (NNSA)
Building the STELLA collaboration and defining a strategy

- 1st Design Characteristics of a Novel Linear Accelerator for Challenging Environments, November 2016, CERN
- 2nd Bridging the Gap Workshop, October 2017, CERN
- 3rd Burying the Complexity Workshop, March 2018, Manchester

- 4th Accelerating the Future Workshop, March 2019, Gaborone
• Not all failures and repairs are created equal
• Nigeria has far longer repair times than in the UK, the repair hub is normally in a different continent or South Africa and maintenance is often not to the same standard
• Interestingly Botswana which is a fairly affluent country and pays for manufacturer’s warranty, service and repair has similar downtime with more faults to LMICs
• MLC (multi-leaf collimator) has the most faults but diagnostics, RF and vacuum contribute to the longest downtime
Looking for solutions for building affordable RT

- **Define the problem**
- **Gather information** from African hospitals/facilities regarding challenges experienced in providing radiotherapy in Africa compare these to data from **HIC**.
- **Identify** the challenges from those who live with them day-to-day
- **Create design specifications** for a radiotherapy machine to meet these challenges for an improved design
- Assess applications of **ML, AI and use of cloud-computing** in African and LMIC settings
- Create **conceptual design report** for the radiotherapy system to enable technical design and prototyping in next phase

Manjit Dosanjh, CERN-IPAC, 27.06.2022
### STELLA Questionnaire

#### Overview

- We asked 36 questions in 5 key areas shown in the table to at least one facility in all African countries with RT access.
- Also sent the survey to facilities in the UK, Canada and the USA, for comparison.
- We examined: the LINAC model, environment, services, subsystems, treatment and imaging.

<table>
<thead>
<tr>
<th>Focus</th>
<th>Questions</th>
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<tbody>
<tr>
<td><strong>Model</strong></td>
<td>What manufacturer and model? Year of installation?</td>
</tr>
<tr>
<td></td>
<td>What number of treatments are performed per year on each machine?</td>
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<tr>
<td><strong>Environment</strong></td>
<td>What is the temperature and humidity in the area?</td>
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<td></td>
<td>What is the speed and availability of the internet connection?</td>
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<tr>
<td></td>
<td>How reliable is the electricity supply?</td>
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<td></td>
<td>What is the floor area and ceiling height of the shielded area?</td>
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<td></td>
<td>What photon energy is your shielded area able to safely operate at?</td>
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<tr>
<td><strong>Services</strong></td>
<td>Do you have a service contract? Who provides it? What is the annual cost?</td>
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<tr>
<td></td>
<td>How often does the machine have maintenance/tuning/calibration?</td>
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<td></td>
<td>What type of failures can you repair locally?</td>
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<td></td>
<td>Number of staff available for in-house repairs? Are staff formally trained?</td>
</tr>
<tr>
<td><strong>Subsystems</strong></td>
<td>How do you identify machine faults? Is it easy?</td>
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<tr>
<td></td>
<td>Do you have problems with the vacuum system? How often?</td>
</tr>
<tr>
<td></td>
<td>Do you have problems with the vacuum pump? Do you keep spares? Can you repair locally?</td>
</tr>
<tr>
<td></td>
<td>Do you keep spare RF sources? Can you repair locally?</td>
</tr>
<tr>
<td></td>
<td>Do you have problems with the MLC? Do you keep spares? Can you repair locally?</td>
</tr>
<tr>
<td></td>
<td>Do you have problems with the electron gun? Do you keep spares? Can you repair locally?</td>
</tr>
<tr>
<td></td>
<td>How much down-time do you experience?</td>
</tr>
<tr>
<td></td>
<td>Do you have any software problems?</td>
</tr>
<tr>
<td><strong>Treatment and Imaging</strong></td>
<td>Does your hospital have diagnostic CT near the radiotherapy area?</td>
</tr>
<tr>
<td></td>
<td>Do you use a tilting Couch? How important is this feature?</td>
</tr>
<tr>
<td></td>
<td>How important is it for a LINAC to offer electron treatment mode?</td>
</tr>
</tbody>
</table>

A table highlighting the questions asked on the questionnaire

Manjit Dosanjh, CERN-IPAC, 7.06.2022
Data Obtained from African Countries That Have LINAC-based RT and from HICs

<table>
<thead>
<tr>
<th>Country</th>
<th>Total number of LINACs surveyed</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK</td>
<td>25</td>
</tr>
<tr>
<td>USA</td>
<td>14</td>
</tr>
<tr>
<td>Canada</td>
<td>11</td>
</tr>
<tr>
<td>Switzerland</td>
<td>2</td>
</tr>
<tr>
<td>Jordan</td>
<td>1</td>
</tr>
</tbody>
</table>

Total LINACs surveyed

- HICs: 52
- Africa: 59

Manjit Dosanjh - IPAC 22-17.06.2022
Downtime in weeks comparison African and HICs

Machine downtime (weeks/year)

- HICs
- Africa
Impact of GDP per Capita and Linac Downtime and Mortality
Are staff trained to troubleshoot the LINAC?

- **20/27** (74%) African facilities have staff who have attended a formal training course.
- **18/19** (95%) are supplied by the manufacturer, either on-site or online.

How fast is the internet connection?

- **28/30** (93%) African facilities have a medium or high internet speed (kb/s - Mb/s).
- Bandwidth may vary dramatically between facilities.

A choropleth map of the number of trained staff capable of troubleshooting
What have we established so far with the subsystems?

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>Downtime</th>
<th>Environment</th>
<th>Possible Features</th>
<th>Services and Education</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 47% of facilities experience MLC failures often. 76% have spares. 77% can repair locally.</td>
<td>• Downtime may depend strongly on vacuum pump failure. Make part very robust.</td>
<td>• All bunkers surveyed are protected to at least 6 MV.</td>
<td>• 81% of facilities find the electron mode highly valuable.</td>
<td>• 91% of facilities have a service contract.</td>
</tr>
<tr>
<td>• 46% of facilities have experienced electron gun failure. 53% keep spares. 33% can repair locally.</td>
<td>• Keep the mains supply as stable as possible, e.g. affordable UPS and backup generators.</td>
<td>• Median bunker dimensions: 3.5 m height and floor area 42 m².</td>
<td>• 26% of facilities currently have a tilting couch, many agree it would be a useful feature for advanced treatments.</td>
<td>• 63% of facilities can troubleshoot problems with machine.</td>
</tr>
<tr>
<td>• 55% of facilities have experienced vacuum pump failure. 33% keep spares. 45% can repair locally.</td>
<td>• Complicated software? Aim for no software problems.</td>
<td>• Mean temperature in African bunkers: 22.6 °C.</td>
<td>• 94% of facilities have access to CT imaging close to RT machines. May need to provide this access in countries with no RT access.</td>
<td>• 71% of facilities have staff attend a formal training course.</td>
</tr>
<tr>
<td>If a facility experiences faults with a component, they are more likely to keep spare parts for it.</td>
<td>• A display/log on the machine may be easier to diagnose LINAC problems at the centre, but may not affect downtime compared to remote diagnosis by manufacturer.</td>
<td>• Temperatures may vary significantly throughout the day. Consider optimal operating temperatures of components.</td>
<td>• Consider a tilting couch. Or aim to improve reliability of parts on new machines not old ones.</td>
<td>• 90% of facilities have medium or high speed internet. Consider bandwidth available before opting for a full online training programme.</td>
</tr>
<tr>
<td>If a facility keeps spare parts, they are more likely to have infrastructure in place to repair it.</td>
<td>• Consider a tilting couch. Or aim to improve reliability of parts on new machines not old ones.</td>
<td>• 87% of facilities have a humidity &lt;= medium. Consider optimal operating humidities of components.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ensure facilities have spares and can repair the part, before it has the chance to fail.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Make fault diagnosis simple. A display/log on the machine will help staff easily identify faults.</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Overall Reasons For LINAC Downtime from Survey

- 69% don’t have access to spare RF Sources.
- 65% don’t have access to spare Vacuum Pumps.
- 63% don’t have access to spare Electron Guns.
- 32% don’t have access to spare MLCs.
Summary of Current Findings

- Local repair and access to parts a significant factor determining downtime
- Software problems are a major contributor to downtime
- Frequency and voltage fluctuations also appear important
- Current data suggests - component importance on downtime: Electron Gun, Vacuum Pump, MLC, RF source, Software, Power Fluctuation
Key issues from reviewing the various surveys, data gathering exercises, failure mode data and discussions at workshops
It was clear that a single machine cannot be realised to encompass all aspects.

Categorisation Priorities:

| High Priority | • Staff training and skill requirements to run a RT machine  
|               | • Severities and cost of repairing technical failures  
|               | • Frequency of failures (i.e. component lifetime) |
| Medium Priority | • Making the electrical system robust to fluctuations and minimising the power requirements  
|               | • Robustness to temperature fluctuations and dust  
|               | • Delivering higher dose  
|               | • Initial capital cost and the cost of spare parts |
| Lower Priority | • Size of the machine  
|               | • Total machine lifetime (as opposed to component lifetime)  
|               | • Easy upgradability |
Key Design Choices

- Key design goal is to offer **Higher Availability and Reliability**
- Repairs are difficult & reduce availability
  - Choice of design and components to improve lifetime
  - Choose components that can be replaced in house with less-expensive spares
  - Use of machine learning to predict faults in advance to protect the machine and order spares
  - Use of AI to identify the cause of faults that have happened
  - Can we simplify the MLCs
Where are we now?

- Gathered information from African hospitals/facilities regarding challenges faced in providing radiotherapy in Africa
- Identified the challenges with those who live with them day-to-day
- Created design specifications for a radiotherapy machine to meet these challenges for an improved design
- Assessing applications of ML, AI and use of cloud-computing in African and LMIC settings
- Created conceptual design report for the radiotherapy system completed to enable technical design and prototyping in next phase
- Securing funding for building and testing prototype
A suitable Low-energy Linear electron accelerator is being developed which matches identified needs, incorporating modern optimization processes and technologies able to provide robust operation and modularized implementation:

- Electron beam source
- Linear accelerator
- RF power source
- Beam delivery system

Developing a prototype solution for a cost-effective treatment:

- Simpler installation
- Robust operation
- Easier to maintain
- Reduced cost
- Remote diagnostics and fault/breakdown detection
STEELA: A Unique Collaboration

Pillar I
New LINAC Prototype

Pillar II
Software Integrated Platform

Pillar III
Training & Mentoring

Project STEELA
Ultimate Goal

- Robust, modular, reliable and easier to use machines

- Are affordable
  - Reduce Capital cost
  - Reduce Operating costs
  - Reduce Service and Maintenance costs
  - Reduce Number of experts needed
  - Increase Number of treated patients per year

- With the aim to
  - Improve patient through-put
  - Increase effectiveness
  - Decrease running cost, staff cost, machine cost
  - Expand access to RT
This work would not be possible without the great collaborators, so a huge thank you to ICEC, ITAR, STELLA and SEEIIIST teams

Especially to:

• Deepa Angal-Kalinin and Peter MacIntosh - UKRI STFC
• Graeme Burt - Lancaster University
• Norm Coleman, Donna O’Brien, and David Pistenmaa and Eugenia Wendling - International Cancer Expert Corps
• Taofeeq Ige, Abuja, Nigeria
• Suzie Sheehy, Oxford and Melbourne
• Petya Georgieva, Vesna Gershan, Mimoza Ristova from SEEIIIST

Thank you for listening