Targeted radionuclide therapy

Targeted radionuclide therapy has the potential to selectively deliver radiation to diseased cells with minimal toxicity to surrounding tissues.

M Sathekge, MB ChB, MMed (Nuclear Medicine), PhD

Department of Nuclear Medicine, University of Pretoria and Steve Biko Academic Hospital, Pretoria, South Africa

Corresponding author: M Sathekge (mike.sathekge@up.ac.za)

The goal of targeted radionuclide therapy is to selectively deliver radiation to cancer cells and/or diseased tissue with minimal toxicity to surrounding normal tissues. The basis for successful radionuclide therapy is a theranostic approach that integrates diagnostic testing for the presence of a molecular target for which a specific treatment/drug is intended (Fig. 1). Theranostics is a revolutionary approach that promises improved therapy selection on the basis of specific molecular features of disease, greater predictive power for adverse effects due to improved patient-specific absorbed dose estimates, and new ways to objectively monitor therapy response.[1,2] Currently, radionuclide therapy remains an important treatment option because ionising radiation from radionuclides can kill cells and inhibit growth in the benign and cancerous lesions that result from proliferative diseases. Radiation kills cells by damaging the DNA in the cell nucleus, thereby inhibiting cellular reproduction. Rapidly developing studies also demonstrate the beneficial effect of combining radionuclide therapy with chemotherapy.[1]

The objective of this article is to introduce the reader to the benefits of targeted radiotherapy, also known as molecular theranostics, to improve patient management. The article highlights evidence-based radionuclide therapy, which is available in South Africa for thyroid cancer, neuro-endocrine tumours, liver tumours (primary and secondary), non-Hodgkin’s lymphoma, and bone metastases, and for treating other non-cancerous diseases. A comprehensive review of the pathology and theranostic targets is beyond the scope of this article, and the reader is referred to reviews in related subjects.

Theranostics is a revolutionary approach that promises improved therapy selection on the basis of specific molecular features of disease, greater predictive power for adverse effects due to improved patient-specific absorbed dose estimates, and new ways to objectively monitor therapy response.

Targeting mechanism/radiopharmaceuticals

The process of tailoring therapy for a patient is based on selecting appropriate radiopharmaceuticals and mechanisms. The commonly employed radiopharmaceuticals and mechanisms are summarised in Table 1. Common examples of patient selection criteria for targeted radionuclide therapy are shown in Table 2.[3]

Table 1. Available radionuclide therapy in oncology

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Physical half-life (days)</th>
<th>Emission</th>
<th>Maximum range (mm)</th>
<th>Radiopharmaceutical</th>
<th>Targeting mechanism</th>
<th>Indications</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-131</td>
<td>8.04 Beta, gamma</td>
<td>4</td>
<td>I-131 as iodide</td>
<td>Thyroid hormone synthesis</td>
<td>Differentiated thyroid cancer</td>
<td></td>
</tr>
<tr>
<td>Lu-177</td>
<td>6.7 Beta, gamma</td>
<td>1</td>
<td>Lu-177 DOTATATE</td>
<td>Somatostatin-receptor binding</td>
<td>Neuro-endocrine tumours</td>
<td></td>
</tr>
<tr>
<td>Y-90</td>
<td>2.7 Beta</td>
<td>12</td>
<td>Y-90 DOTATATE</td>
<td>Somatostatin-receptor binding</td>
<td>Neuro-endocrine tumours</td>
<td></td>
</tr>
<tr>
<td>Y-90</td>
<td>2.7 Beta</td>
<td>12</td>
<td>Y-90 microspheres, SIR-Spheres or TheraSpheres</td>
<td>Intravascular trapping</td>
<td>Liver metastases Hepatocellular carcinoma</td>
<td></td>
</tr>
<tr>
<td>Y-90</td>
<td>2.7 Beta</td>
<td>12</td>
<td>Y-90 ibritumomab tiuxetan (Zevalin)</td>
<td>CD20 antigen binding</td>
<td>Non-Hodgkin’s lymphoma</td>
<td></td>
</tr>
<tr>
<td>I-131</td>
<td>8.04 Beta, gamma</td>
<td>4</td>
<td>I-131 tositumomab (Bexxar)</td>
<td>CD20 antigen binding</td>
<td>Non-Hodgkin’s lymphoma</td>
<td></td>
</tr>
<tr>
<td>I-131</td>
<td>8.04 Beta, gamma</td>
<td>4</td>
<td>I-131 MIBG</td>
<td>Active transport and intracellular storage</td>
<td>Bone pain palliation</td>
<td></td>
</tr>
<tr>
<td>Sm-153</td>
<td>1.95 Beta, gamma</td>
<td>3.1</td>
<td>Sm-153 EDTMP</td>
<td>Chemo-adsorption</td>
<td>Bone pain palliation</td>
<td></td>
</tr>
<tr>
<td>Sr-89</td>
<td>50.5 Beta</td>
<td>8</td>
<td>Sr-89 chloride</td>
<td>Calcium analogue</td>
<td>Bone pain palliation</td>
<td></td>
</tr>
</tbody>
</table>

MIBG = meta-iodobenzylguanidine; EDTMP = ethylene-diamine-tetramethylene-phosphonic acid.
Radioactive iodine therapy: Thyroid cancer

The therapeutic use of iodine-131 (I-131) is a well-established procedure that supplements surgery in differentiated thyroid cancer (follicular and papillary).

The benefits of I-131 therapy include:
- facilitating the interpretation of subsequent serum thyroglobulin levels
- increasing the sensitivity of detection of locoregional and/or metastatic disease on subsequent follow-up whole-body radioactive iodine scans
- maximising the therapeutic effect of subsequent treatments
- allowing a post-ablation scan to help identify additional sites of disease that were not identified pre-ablation
- decreasing recurrence and disease-specific mortality for both known and unknown microscopic and metastatic disease.

To achieve these benefits, theranostics of thyroid cancer is performed using I-123 or I-131 for diagnostics, with single photon emission computed tomography/computed tomography (SPECT/CT) (Fig. 2), and I-131 for personalised radionuclide therapy.

Long-term follow-up confirms that patients with I-131-avid metastases have significantly better 5- and 10-year survival rates than those whose metastases do not take up I-131 and cannot be treated this way.

Accumulated evidence from clinical experience indicates that partial and complete responses may be achieved in almost 50% of patients, and that the duration of the therapy response is more than 40 months. The patients’ self-assessed quality of life also improves significantly after treatment with Lu-177-DOTATATE. Lastly, compared with historical controls, patients treated with Lu-177-DOTATATE show an increase in overall survival of several years from the time of diagnosis. Side-effects of PRRNT are typically seen in the kidneys. These, however, are usually few and mild provided adequate protective measures such as amino acid infusion are undertaken.

Selective internal radiation therapy: Liver cancer (primary and secondary)

Selective internal radiation therapy (SIRT) or trans-arterial radio-embolisation using Y-90-labelled microspheres is a treatment option for patients with unresectable primary and secondary liver malignancies. This technique involves the intra-arterial injection of commercially available Y-90-labelled microspheres (SIR-Spheres and TheraSpheres) via the hepatic artery or one of its side branches. Liver metastases are primarily fed via the hepatic artery, whereas normal liver tissue is fed primarily via the portal vein. Up to 3 times more hepatic arterial vessels surround liver tumours than normal liver tissue. Therefore, a

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**Table 2. Common examples of patient selection criteria for targeted radionuclide therapy**

<table>
<thead>
<tr>
<th>Indications</th>
<th>Minimum haematological and biochemical criteria</th>
<th>Contraindications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inoperable/failed conventional therapy</td>
<td>Hb &gt;10 g/l</td>
<td>Pregnancy/lactation</td>
</tr>
<tr>
<td>Good performance status: self-caring</td>
<td>WCC &gt;3x10^9/l</td>
<td>Inability to comply with radiation protection instructions</td>
</tr>
<tr>
<td>Confirmed histology</td>
<td>Platelets &gt;100x10^9/l</td>
<td>Short life expectancy</td>
</tr>
<tr>
<td>Positive uptake on a diagnostic scintiscan</td>
<td>Urea &lt;10 mmol/l</td>
<td>Renal failure</td>
</tr>
<tr>
<td>Stop/suspend interfering treatment/drugs</td>
<td>Creatinine &lt;160 µmol/l</td>
<td>Liver failure</td>
</tr>
<tr>
<td></td>
<td>GFR &gt;40 ml/min</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biochemical tumour marker</td>
<td></td>
</tr>
</tbody>
</table>

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**Peptide receptor radionuclide therapy: Neuro-endocrine cancer**

Peptide receptor radionuclide therapy (PRRNT) is the treatment of choice in adult patients with neuro-endocrine cancer who are inoperable, who have residual disease following surgery or other ablative therapy, or who have metastases. PRRNT is based on the fact that about 70% of these tumours express somatostatin receptors (especially subtype 2) on the cell surface, which constitutes an excellent therapeutic target.

In PRRNT, a receptor ligand (i.e. a somatostatin analogue) is bound to a radioactive isotope (normally Lu-177 or Y-90). Commonly used radiopharmaceuticals are Lu-177-DOTATATE and Y-90-DOTATATE. The radionuclide is thereby bound to the tumour cells by these somatostatin analogues, which decay, with the resulting radiation damaging the surrounding cells.

Positive somatostatin receptor scintigraphy with In-111 or Tc-99m-octreotide or, even better, with positron emission tomography/computed tomography (PET/CT) using Ga-68-DOTATATE, is an important tool for predicting the efficacy of PRRNT, and also for the assessment of the response to PRRNT (Fig. 1). PRRNT is not useful for the treatment of G3 (poorly differentiated) tumours. These tumours have high expression of Ki67 and are fluorodeoxyglucose (FDG)-PET/CT positive, but negative for a Ga-68-DOTATATE PET/CT.

Accumulated evidence from clinical experience indicates that partial and complete responses may be achieved in almost 50% of patients, and that the duration of the therapy response is more than 40 months. The patients’ self-assessed quality of life also improves significantly after treatment with Lu-177-DOTATATE. Lastly, compared with historical controls, patients treated with Lu-177-DOTATATE show an increase in overall survival of several years from the time of diagnosis. Side-effects of PRRNT are typically seen in the kidneys. These, however, are usually few and mild provided adequate protective measures such as amino acid infusion are undertaken.

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**Selective internal radiation therapy: Liver cancer (primary and secondary)**

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selective high dose (i.e. >75 Gy) to tumours can be achieved with minimal damage to normal hepatocytes, which have a tolerance to radiation doses of up to 35 Gy. Patient selection requires a meticulous work-up with an initial angiographic evaluation to maximise therapeutic response and minimise its side-effects. This is primarily to document the visceral anatomy, provide information on perfusional flow characteristics of the targeted vascular territory, identify anatomical variants, and isolate the hepatic circulation by occluding extrahepatic vessels. A pre-treatment hepatic artery Tc-99m macroaggregate of albumin (MAA) scan is performed to detect any extrahepatic shunting to the lung or gastrointestinal tract. Excessive shunting to the lungs that would result in a >30 Gy lung dose on a single administration excludes the patient from SIRT.[9]

Given the possibility of non-target deposition of microspheres, prophylactic embolisation of all extrahepatic vessels at the time of MAA assessment is performed to avoid extrahepatic deposition of microspheres. Since these vessels/organs can revascularise quickly, SIRT is performed within 2 weeks of the initial angiographic evaluation and prophylactic embolisation.

Increasing evidence confirms that early response assessment to SIRT using F-18-FDG PET/CT is superior to morphological imaging, demonstrating a correlation with tumour markers and significantly predicting progression-free survival in patients with liver malignancies (Fig. 3).

Clinical trials have shown that median survival after SIRT is about 65 weeks, and disease-control rates are 35 - 88%, depending on the criteria for response assessment.[9]

Radio-immunotherapy: Non-Hodgkin's lymphoma

Radio-immunotherapy (RIT) is well tolerated and effective in the treatment of follicular B-cell lymphomas expressing the CD20 epitope in first-line or subsequent lines of therapy.

RIT is a form of targeted radionuclide therapy that uses a monoclonal antibody to deliver localised radiation. RIT is given along with sufficient unlabelled antibody to saturate the non-tumour antibody binding sites, and to potentially evoke a direct antitumour effect.

Using an anti-CD20 antibody as a delivery device to target the follicular B-cell lymphomas expressing the CD20 epitope with a radionuclide (Y-90/I-131), amplifies the cytotoxic effect via a radiation cross-fire effect, whereby ionising radiation has an effect on neighbouring cells in a spherical zone surrounding the deposited radionuclide.[11] Currently, 2 radiolabelled antibodies are available for treatment of follicular non-Hodgkin's lymphoma, Y-90 ibritumomab tiuxetan (Zevalin) and I-131 tositumomab (Bexxar). Dose-limiting toxicity for both radiolabelled antibodies results in reversible bone marrow suppression. Again, 18-F-FDG PET/CT is superior to morphological imaging in demonstrating response to therapy (Fig. 4).
Data demonstrate that RIT is effective, with an overall response rate of approximately 80% and a complete response of approximately 30% in patients who are refractory to unlabelled anti-CD20 immunotherapy and chemotherapy, or have relapsed after these therapies.\[11\]

Despite impressive clinical trial data, these products have been underutilised because of the complexity of treatment co-ordination and concerns regarding reimbursement.

**Selective internal radiation therapy (SIRT) with Y-90-labelled particles is an effective and well-tolerated treatment for non-resectable primary and secondary liver neoplasm.**

I-131-meta-iodobenzylguanidine: Endocrine tumours

I-131-meta-iodobenzylguanidine (MIBG) has been shown to be effective in chromaffin tumours (neuroblastoma, phaeochromocytoma, and paraganglioma) as well as for carcinoid and medullary thyroid carcinoma. Uptake of MIBG, a norepinephrine analogue, in tissue
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Table 3. Commercially available radionuclides for radiosynoviorthesis

<table>
<thead>
<tr>
<th></th>
<th>Y-90</th>
<th>Re-186</th>
<th>Er-169</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical half-life (days)</td>
<td>2.7</td>
<td>3.7</td>
<td>9.5</td>
</tr>
<tr>
<td>Emission</td>
<td>Beta</td>
<td>Beta, gamma</td>
<td>Beta</td>
</tr>
<tr>
<td>Maximum range (mm)</td>
<td>12</td>
<td>3.7</td>
<td>1</td>
</tr>
<tr>
<td>Compound</td>
<td>Citrate</td>
<td>Sulphide</td>
<td>Citrate</td>
</tr>
<tr>
<td>Joints</td>
<td>Large: knee</td>
<td>Medium: shoulder, elbow, wrist, superior hip and inferior tarsal joint</td>
<td>Small: MCP, PIP, DIP, MTP</td>
</tr>
</tbody>
</table>

MCP = metacarpophalangeal; PIP = proximal interphalangeal; DIP = distal interphalangeal; MTP = metatarsophalangeal.

Bone-seeking radionuclides: Metastatic bone pain
Pain palliation with bone-seeking radiopharmaceuticals has proved to be an effective and cost-effective management tool in patients with metastatic bone pain. Radiopharmaceuticals bind to the bone matrix in areas of increased bone turnover due to a metastatic response. Beta-rays from the specific radionuclide, bound to its carrier ligand, result in the therapeutic effect. At least 7 bone-seeking radionuclides have shown evidence of both safety and efficacy in reducing pain from diffuse skeletal metastases. All have their own characteristics. The radiopharmaceuticals samarium-153-ethylene-diamine-tetramethylene-phosphonic acid (Sm-153-EDTMP) and strontium-89-chloride, which are widely approved and commercially available, are discussed briefly. Patients with a positive bone scan using technetium-99m methylene-diphosphonate (Tc-99m-MDP) are indicated for treatment if they qualify in terms of the general indications and contraindications as defined in Tables 1 and 2.

In most cases, bone marrow toxicity is limited and reversible, which makes repetitive treatment relatively safe. Several studies have shown encouraging results using bone-seeking radiopharmaceuticals, with an overall reported pain response rate of ±70 - 80% of patients. This systemic form of radionuclide therapy is simple to administer and complements other treatment options. It has been associated with marked pain reduction, improved mobility, reduced dependence on analgesics, and improved performance status and quality of life.

Radioactive iodine therapy: Hyperthyroidism
Thyrotoxicosis can be diagnosed by high serum levels of thyroxine and tri-iodothyronine and a low serum level of thyroid-stimulating hormone. Hyperthyroidism is confirmed by high isotope (I-131 or Tc-99m) uptake by the thyroid gland, while in thyroiditis it will be

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Radiosynoviorthesis
Radiosynoviorthesis means the restoration (orthesis) of the synovial by radionuclides. Through local application of radioactive agents an attempt is made to influence the synovial process favourably as an alternative to surgical synovectomy. Intra-articular injected beta-emitting radionuclides are indicated in chronic synovitis with recurrent joint effusions in rheumatoid arthritis, seronegative spondyloarthritides, villonodular synovitis after surgery and haemarthrosis in haemophilia. The value of radiosynoviorthesis in activated osteoarthrosis is variable. The technique requires appropriate selection of the radiopharmaceutical agent, which should have specific properties. The radiation energy should be sufficient to penetrate and ablate the synovial tissue, but not so great as to damage underlying articular cartilage or overlying skin (Table 3). In 40 - 80% of cases, inflammation parameters such as pain, local hyperthermia, swelling and joint effusion decrease within 3 - 4 months. If a radiosynoviorthesis is not satisfactory, it can be repeated within 6 months.
Currently, these products are underutilised owing to lack of information and concerns about reimbursement.

Acknowledgement. My thanks to the staff members of the Department of Nuclear Medicine at Steve Biko Academic Hospital and NTP Radioisotopes (SOC).

References

Summary

• Theranostics epitomises the inseparability of diagnosis and therapy.
• Radionuclide therapy uses radioactive isotopes administered either orally or intravenously to deliver highly targeted therapy for a range of disorders, enabling the delivery of a high dose to the target, while minimising normal tissue toxicity.
• Radioactive iodine therapy for differentiated thyroid cancer and hyperthyroidism is the most commonly employed targeted radionuclide therapy.
• Peptide receptor radionuclide therapy is an effective treatment option for patients with well-differentiated somatostatin receptor-expressing neuro-endocrine tumours. Considering the mild side-effects, it may well become the first-line therapy in patients with metastatic or inoperable neuro-endocrine tumours.
• Selective internal radiation therapy (SIRT) or trans-arterial radio-embolisation using Y-90-labelled microspheres is a treatment option for patients with unresectable primary and secondary liver malignancies.
• Radiolabelled antibodies against CD20-positive cells (radio-immunotherapy) is an attractive option for the treatment of patients with non-Hodgkin’s lymphoma, which can be adapted to individual prognosis and treatment needs.
• Radiolabelled MIBG is an example of theranostics and remains a useful agent for both diagnosis and therapy of endocrine tumours.
• Systemic radiopharmaceutical therapy is an important treatment option in severe, painful bone metastases that significantly lower patients’ quality of life.
• Radiosynoviorthesis with the nuclides Y-90, Re-186 and Er-169 is an established option for the treatment of persistent synovitis of large, medium and small joints.
• Increasing evidence confirms targeted radionuclide therapy to be effective and safe, and shows an increase in overall survival.