



Position Paper

Radiopharmaceuticals in the elderly cancer patient: Practical considerations, with a focus on prostate cancer therapy

A position paper from the International Society of Geriatric Oncology Task Force



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Abstract Molecular imaging using radiopharmaceuticals has a clear role in visualising the presence and extent of tumour at diagnosis and monitoring response to therapy. Such imaging provides prognostic and predictive information relevant to management, e.g. by quantifying active tumour mass using positron emission tomography/computed tomography (PET/CT). As these techniques require only pharmacologically inactive doses, age and potential frailty are generally not important. However, this may be different for therapy involving radionuclides because the radiation can impact normal bodily function (e.g. myelosuppression). Since the introduction of Iodine-131 as a targeted therapy in thyroid cancer, several radiopharmaceuticals have been widely used. These include antibodies and peptides targeting specific epitopes on cancer cells. Among therapeutic bone seeking agents, radium-223 (²²³Ra) stands out as it results in survival gains in patients with castration-resistant prostate cancer and symptomatic bone metastases. The therapeutic use of radiopharmaceuticals in elderly cancer patients specifically has received little attention. In elderly prostate cancer patients, there may

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be advantages in radionuclides' ease of use and relative lack of toxicity compared with cytotoxic and cytostatic drugs. When using radionuclide therapies, close coordination between oncology and nuclear medicine is needed to ensure safe and effective use. Bone marrow reserve has to be considered. As most radiopharmaceuticals are cleared renally, dose adjustment may be required in the elderly. However, compared with younger patients there is less, if any, concern about adverse long-term radiation effects such as radiation-induced second cancers. Issues regarding the safety of medical staff, care givers and the wider environment can be managed by current precautions.

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1. Introduction

Diagnostic radiopharmaceuticals are generally pharmacologically inactive and given only in relatively small doses needed for imaging. Such agents are considered to have no measurable pharmacodynamic impact [1]. For these reasons, there is little concern about specific toxicity problems arising with age, although the practicalities of imaging elderly patients need to be considered. In contrast, with therapeutic radiopharmaceuticals, the desired clinical benefit arises from the effects of radiation on the tumour, and courses of treatment may involve frequent administration. In this context, both age-related changes in tissues, such as bone marrow, and questions of altered drug clearance arise.

A Task Force of the International Society of Geriatric Oncology (SIOG) considered practical recommendations on the use of radiopharmaceuticals, both diagnostic and therapeutic, in elderly cancer patients. This increasingly important issue has not previously been reviewed from the perspective of elderly patients. Such a perspective is important because physiological reserves typically decline with age; many elderly patients have significant comorbidities; and there is increased risk of interactions with drugs taken for concomitant disease [2,3].

Systemically administered therapeutic radiopharmaceuticals are used in thyroid cancer (an area in which there is more than 50^o years of experience), in neuroendocrine tumours, in non-Hodgkin lymphoma and in myeloproliferative diseases. However, these tumours are relatively infrequent, even in the elderly.

The most common tumours (lung, colorectal, breast and prostate), show a steeply rising incidence and mortality with increasing age (Fig. 1) [4]. Among these four tumours, the risk of skeletal involvement is high in three: in advanced stages of the disease, bone metastases are present in 47–85% of breast cancer patients, 32–60% of those with lung cancer, and 33–85% of prostate cancer patients [5]. Given the recent increased interest in radionuclides in patients with bone metastases from castration-resistant prostate cancer (CRPC), and as more than 90% of them have skeletal metastases

[6], discussion of the therapeutic use of radiopharmaceuticals focussed on this area.

The general principles underlying radionuclide use in the elderly are likely to be similar to those in younger patients. However, elderly patients have been under-represented in clinical trials, despite the fact that the majority of cancers—and hence of treatment—is in precisely these patients. Hence, as in most areas of oncology, specific data on the efficacy and toxicity of radionuclides in these populations are limited.

Task Force members conducted literature searches in their areas of expertise. We make no attempt to formally assign levels of evidence to recommendations. They should be considered those of an expert group and as the basis for further discussion. The recommendation that more elderly patients should be included in trials is an obvious starting point.

2. Age and frailty: general considerations

While chronological ageing is uniform and relentless, biological ageing is not. The main relevant factors are: (1) functional losses, including those relating to cognition; (2) the effects of declining physiological reserves on resistance to toxicity and on drug handling; and (3) the implications of comorbidities and associated polypharmacy.

The broad concept of frailty, defined as vulnerability in the face of a stressor, is of interest to clinicians assessing the likely side-effects of therapy [7]. Functional status and the presence of comorbidities are the most readily available guides to patients who are especially vulnerable to adverse effects of treatment.

Means of assessing the overall fitness of elderly patients and the likely toxicity of chemotherapy have been developed [2,8,9]. Although they have not been assessed in the context of radiopharmaceuticals, such tools may help predict any toxicity in elderly patients.

In the setting of prostate cancer specifically, a recent International Society of Geriatric Oncology (SIOG) Task Force [3] has advocated initial screening for cognitive impairment, to establish patient competence in making decisions, followed by brief evaluation of health status using the validated G8 screening tool. Abnormal

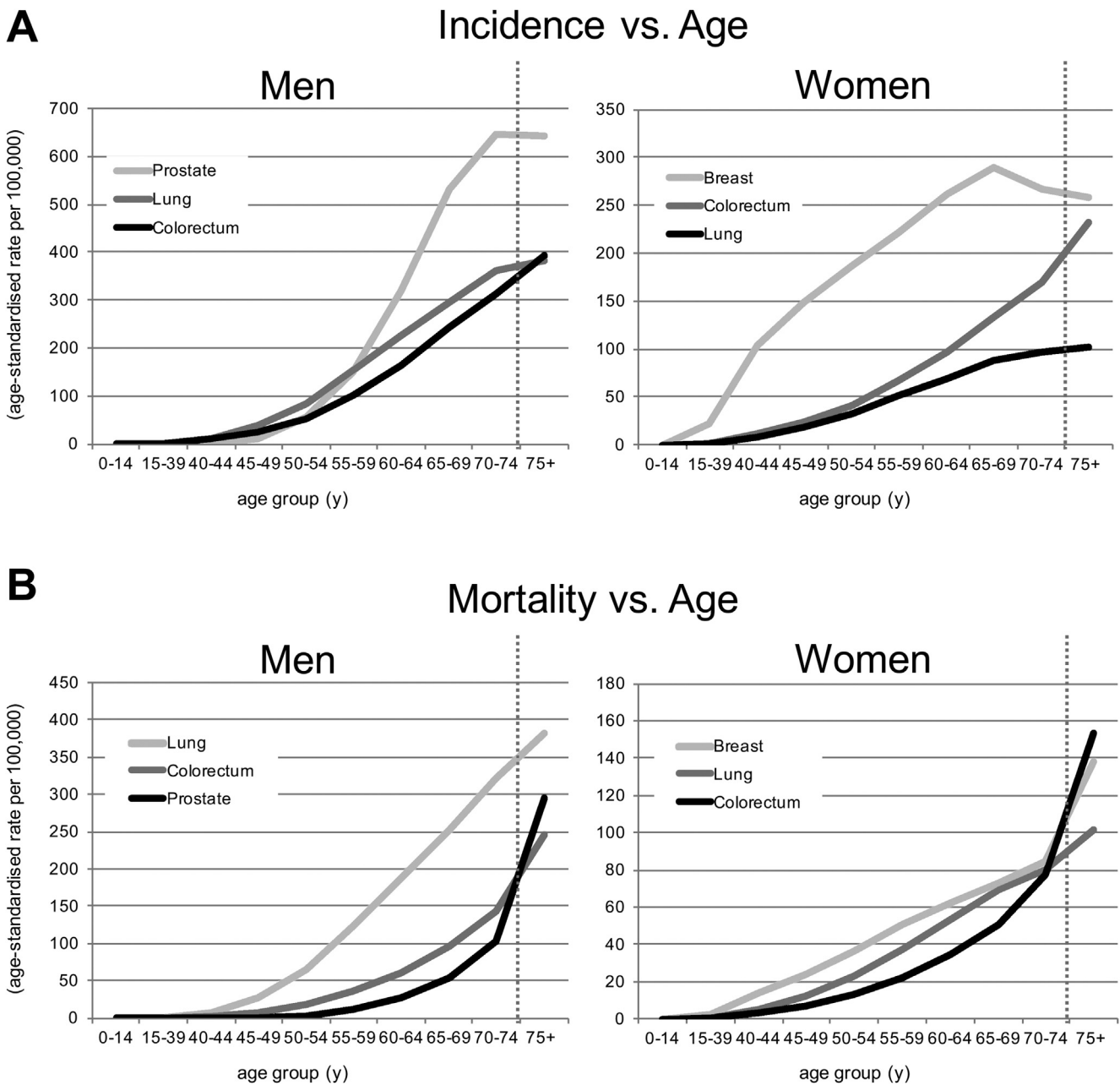


Fig. 1. (A) Incidence and (B) mortality of the three most frequently encountered cancers in Europe in men and women according to age (Data from [<http://globocan.iarc.fr> GLOBOCAN 2012, last accessed on September 2014, 21], IARC®).

scores on the G8 should lead to a simplified geriatric assessment that evaluates comorbid conditions, dependence and nutritional status (by estimation of weight loss).

Also in the prostate cancer setting, the potential importance of comorbidities is illustrated by the trial in which D’Amico *et al.* randomised 206 men to radiotherapy (RT) alone or RT plus androgen suppression [10]. For the group as a whole, combined treatment was associated with significantly reduced all-cause mortality (30 versus 44 deaths, $p = 0.01$). However, among men with moderate or severe comorbidity, there was a trend

in the opposite direction with more deaths in the RT plus androgen suppression group than in those treated with RT alone (19 versus 13 deaths, $p = 0.08$). While acknowledging that they derive from a subgroup analysis, such data make a strong case for distinct trials to be conducted in patients with comorbidities.

Most radiopharmaceutical studies do not include specific measures of comorbidity, frailty or functional loss. In their absence, the potential impact of such agents on less fit patients must be extrapolated from the healthier patients who were enrolled, or from studies of other agents which did include less fit patients.

3. Radiopharmaceuticals in imaging

3.1. Diagnosis and staging

The availability of information from radionuclide imaging contributes greatly to personalised cancer treatment. Here, we do not seek to compare the merits of different imaging techniques, but consider them from the perspective of the elderly.

In elderly Medicare patients (mean age 73°years), analysis of registry data from more than 20,000 imaging studies demonstrated that having information from-fluorine-18- fluorodeoxyglucose (¹⁸F-FDG) positron emission tomography computed tomography (PET-CT) led to a major change in management in 30–40% of cases and a minor change in another 10–30% [11]. The report covered the role of imaging in diagnosis, staging, restaging and investigation for suspected recurrence and monitoring response to therapy. It concluded that physicians frequently change their intended management of elderly cancer patients on the basis of PET scans, and that this applies across the range of its uses. However, it is notable that only 5% of patients in the study were aged 85°years or more.

Other important applications include guiding and selecting biopsy sites, identifying tumours in patients with rising markers, guiding radiation therapy, and distinguishing tumour recurrence or residual tumour from post therapy changes (such as fibrosis and necrosis) on CT.

In several tumours, imaging with a variety of radiopharmaceuticals is an integral part of diagnosis. Although extremely rare, adverse allergic reactions have been reported with ¹⁸F-FDG [12–14]. Overall, however, diagnostic nuclear medicine is associated with an exceptionally low risk of toxicity as, at the dose administered, the agents are not pharmacodynamically active. In a prospective questionnaire study conducted over 4°years covering 80,000 radiopharmaceutical administrations for PET in 22 participating institutions, Silberstein found no reports of adverse reactions [15]. In an earlier 5-year prospective study in 18 institutions, only 18 adverse reactions were recorded in more than 780,000 radiopharmaceutical administrations [16]. Of these reactions, ten were rashes. None of the patients involved required hospitalisation or had significant sequelae.

Use of diagnostic radiopharmaceuticals does not require assessment of renal insufficiency; and although diabetic patients should have a glucose level that is well controlled on the day of the ¹⁸F-FDG PET, comedication with metformin is not a potential problem. In both cases, this situation is different from that with CT involving contrast media.

In general, no clinically relevant issues arise relating to the particular vulnerability of elderly patients, nor to

the increased risk of drug interaction or toxicities related to comorbidities. Furthermore, compared with children and young adults, the long-term risks for radiation-induced second cancers associated with radiation exposure due to diagnostic medical procedures are unlikely to be relevant in elderly patients with more limited life expectancy.

However, there are certain practical considerations relating, for example, to technetium-99m-bisphosphonate bone scintigraphy, which is still the standard method of staging in advanced prostate cancer [17,18]. Although safe, the length of time that may be required for scanning can be difficult for elderly patients, especially for those with musculoskeletal problems who find prolonged immobility uncomfortable and even painful. In frail elderly patients, it is worth considering an increase in the dose of isotope administered to allow shortening of the scanning time, thereby minimizing patient discomfort.

3.2. Prognosis and treatment monitoring

Prognosis is of concern with all patients but is particularly relevant to the elderly in whom expected benefits and toxicity must be balanced in the light of concomitant disease and competing causes of death. Information from radionuclide scanning can contribute considerably to management decisions. If used appropriately, it may avoid the need for other investigations, as well as unnecessary treatment. Such an outcome is desirable for reasons of patient comfort, quality of life and cost.

The quantification of overall tumour load and, more importantly, of biologically aggressive tumour is relevant to a variety of cancers. However, whether or not it is a predictor of poor outcome depends on the tumour type and on the treatments available. In colorectal and squamous cell lung cancer, a high standardised uptake volume (SUVmax) suggests poor prognosis [19]. Quantitative analysis of FDG PET has value in predicting relapse-free (RFS) and overall survival (OS) independently of tumour-node-metastasis (TNM) staging in non-small cell lung cancer [20]. Also, in lymphoma FDG-PET has become a standard imaging method for therapy monitoring, providing prognostic and predictive information. A computer programme to aid such quantification is being developed to calculate its predictive value [21].

FDG PET can identify previously unknown second primary tumours (which are present in about 1–2% of patients) or distant metastases (Fig. 2), as in head and neck cancer [22]. Knowing their presence may influence the timing and aggressiveness with which the initial or primary cancer is treated.

FDGPET also allows identification of patients who fail to respond to initial cycles of neoadjuvant chemotherapy. Such techniques seem especially useful in

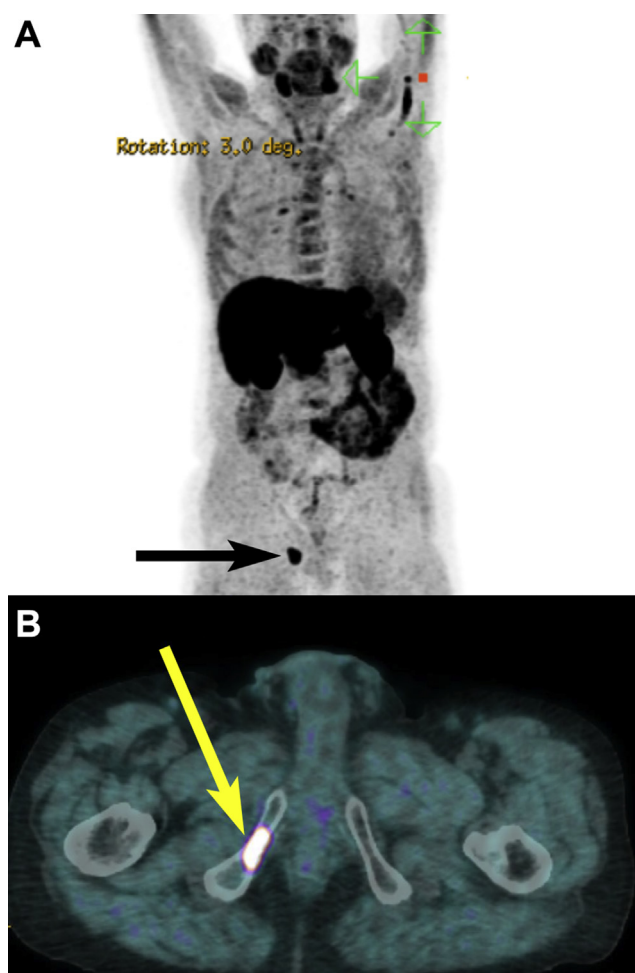


Fig. 2. A 69-year old patient with biochemical relapse from prostate cancer (Gleason 7, PSA3 ng/ml) showing a single site of bone metastasis on the right ischium with ¹⁸F-choline PET not visible by bone scintigraphy. The patient received isolated radiation therapy and the PSA decreased to <0.05 ng/ml). He has been relapse-free for 24 months.

cancers including those of the head and neck, oesophagus, bladder and lung [23–27].

Other radiopharmaceuticals are relevant to a specific cancer-related process. Use of fluorine-18-FLT, a

marker for tumour cell proliferation, can be valuable e.g. in monitoring the treatment of lymphoma or the effectiveness of radiotherapy and in adjusting the treated volume [28,29].

Such adaptive radiation therapy allows treatment to be confined to a smaller area at increased dose when a tumour has been reduced in size, or stopped or changed in those who are clearly not responding [30]. Table 1.

In castration-resistant prostate cancer (CRPC) patients on systemic treatment, current European Society for Medical Oncology (ESMO) guidelines recommend regular imaging to monitor disease response or progression, although their recommendation is supported by a relatively low level of evidence (V) [31]. At the time of writing, the latest European Association of Nuclear Medicine (EANM) guidelines were still in preparation. FDG PET CT scan is not recommended for prostate cancer except for aggressive form of disease, while bone scan using ^{99m}Tc-labeled diphosphonates is still standard [18].

Techniques such as sodium ¹⁸F PET-CT may prove valuable in relation to ²²³Ra treatment [32]. At present, a standard bone scan is still routine to select eligible patients. In the individual patient, and in the absence of trial evidence, practice in relation to imaging should be guided by factors such as the goal of treatment, prostate-specific antigen (PSA) increase and velocity, and clinical suspicion.

Newer agents targeting the prostate-specific membrane antigen (PSMA) are being developed and used clinically based on ⁶⁸Ga and ¹⁸F radioisotopes and have already been shown superior to choline-labeled tracers. These are likely to develop further and play a significant role in CRPC [33,34].

In Europe, gallium-68 (Ga-68)-PSMA-11 PET/CT (PSMA PET/CT) is increasingly used and provides sensitivity and specificity superior to that of F-18-FCH, although it is not yet approved by the European Medicines Agency (EMA). The technique has potential as a means of triaging patients to be treated by Ra-223 or lutetium-177 (Lu-177)-PSMA [35]. ¹¹C- or ¹⁸F-choline radiopharmaceuticals have proved useful in detecting

Table 1

Concerns about radiopharmaceuticals in diagnosis, monitoring and therapy and their potential relevance to the elderly cancer patient.

	Diagnosis and monitoring, including for relapse	Therapy
Age-related alterations in pharmacokinetics or pharmacodynamics resulting in reduced efficacy or increased toxicity	For FDG, check glucose levels	Minor for ²²³ Ra, which is excreted predominantly in faeces. But renal function is relevant for other therapeutic radionuclides
Interaction with drugs being taken for comorbid conditions	None	Minor, though certain beta-blockers, for example, decrease MIBG targeting
Effects on reproductive function, foetal toxicity and breast feeding	Not applicable	Not applicable
Risk of long-term radiation toxicities such as induction of treatment-related solid and haematological cancers	None	Less concern in elderly populations than in younger patients

Fluorodeoxyglucose (FDG); radium-233 (²²³Ra); ¹³¹I-metaiodobenzylguanidine (MIBG).

Table 2
Summary of current recommendations relevant to use of radiopharmaceuticals in metastatic castration-resistant prostate cancer (mCRPC).

Source	Setting	Recommendations	Evidence level grade	Reference
ESMO	First line in mCRPC	Docetaxel	I A	Parker <i>et al.</i> , 2015 [31]
		For asymptomatic or mildly symptomatic disease: abiraterone, enzalutamide or sipuleucel-T	I A II B	
	Second line (post docetaxel)	For bone predominant, symptomatic disease without visceral metastases: ²²³ Ra	I A	
		Abiraterone, cabazitaxel, enzalutamide, and ²²³ Ra (in those without visceral disease)	I A	
European Association of Urology		No clear-cut recommendation can be made for the most effective drug for secondary treatment (i.e. hormone therapy or chemotherapy)	3 A	Mottet <i>et al.</i> , 2016 [54]
	Candidates for cytotoxic therapy Relapse following docetaxel	Offer docetaxel 75 mg/m ² every 3 weeks.	1a A	
		Offer further life-prolonging treatment options, which include cabazitaxel, abiraterone, enzalutamide and radium-223. Base second-line treatment decisions on pre-treatment performance status, comorbidities and extent of disease.	1a A B	
	Non-specific management	In painful bone metastases, palliate early using radionuclides, external beam radiotherapy and analgesics	1a B	
NCCN	Initial therapy:			NCCN.org v2.2016 [56]
	No visceral metastases	Abiraterone, docetaxel, enzalutamide, or ²²³ Ra (for symptomatic bone mets); or clinical trial; or secondary hormone therapy	Cat. 1	
	Visceral metastases	Docetaxel, enzalutamide; or abiraterone, or mitoxantrone (if not candidate for docetaxel); clinical trial; or secondary hormone therapy	Cat. 1	
	Subsequent systemic therapy:			
	No visceral metastases	For patients with prior exposure to docetaxel, ²²³ Ra is among the 10 options (including docetaxel re-challenge and best supportive care); for patients with prior enzalutamide or abiraterone, ²²³ Ra is among eight options	Cat. 1	
	Visceral metastases	²²³ Ra not among the options		
American Urological Association	Symptoms related to bony metastases; no known visceral disease			AUA 2015 [57]
	No prior docetaxel	²²³ Ra an option in patients with good PS; also an option in selected poor PS patients when PS is directly related to symptoms related to bone mets.	Standard Expert opinion	
	Prior docetaxel	²²³ Ra an option in good PS patients	Standard	
American Society of Clinical Oncology	No prior docetaxel	Continue androgen deprivation indefinitely Offer abiraterone, enzalutamide or ²²³ Ra; may also offer docetaxel/prednisone accompanied by discussion of toxicity risk; and sipuleucel-T if no or minimal symptoms.	Benefit of ²²³ Ra moderate; harm low; evidence strong; recommend-ation strong	Basch E <i>et al.</i> , 2014 [58]
	Prior docetaxel	May offer cabazitaxel with toxicity discussion; or mitoxantrone with discussion of limited benefit and toxicity risk.		

PS: performance status NCCN: National Comprehensive Cancer Network.

biochemical relapse in prostate cancer patients [33]. An example is shown in Fig. 2.

4. Therapeutic radiopharmaceuticals

Age-related dose adjustment is generally not required. If necessary, anaemia should be corrected as part of general supportive care. There are no guidelines specific to the need for transfusions in the haematopoietic support of patients being treated with radiopharmaceuticals. Transfusion should therefore be used at the physician's discretion.

The use of phosphorous-32 (^{32}P) in refractory myeloproliferative diseases such as polycythaemia vera and essential thrombocythaemia should also be acknowledged. Although overshadowed by recent developments, ^{32}P is well tolerated and can be particularly helpful in elderly patients in whom one or two doses provide adequate disease control. In short, established drugs may work well, and especially so in patients with limited life expectancy.

In solid tumour oncology, the archetypical targeted radiopharmaceutical is ^{131}I for the treatment of differentiated thyroid cancer following thyroidectomy. The safety and efficacy of this treatment in both adjuvant and metastatic settings are well established and thoroughly discussed elsewhere [36]. In relation to the elderly, it is worth noting that it may be preferable to raise thyroid stimulating hormone (TSH) levels by injection of recombinant TSH (rTSH) (Thyrogen[®]) pre-treatment rather than by thyroid hormone withdrawal. This avoids a prolonged period of hypothyroidism and the associated risks of depression and reduced metabolism and activity, which may be especially harmful in the elderly. However, this approach is not approved in all countries, and the number of rTSH administrations may be restricted to two in addition to the initial treatment.

Although this article relates mostly to solid tumours, radioimmunotherapy contributes to the treatment of haematological malignancies. Most attention has focussed on CD20-positive non-Hodgkin lymphoma (NHL). Although effective in subgroups of patients, this treatment option is not widely used. In their 2005 review [37], Rao *et al.* concluded that these agents are well tolerated in elderly NHL patients, even though marrow involvement is common. Caution is required if more than 25% marrow is involved, in case of prior marrow-ablative therapy or hypocellular bone marrow (<15%).

There is also evidence for the efficacy of ^{90}Y resin microspheres in the radioembolisation of patients with advanced hepatocellular carcinoma [38]. This may have particular relevance in elderly patients needing to avoid chemotherapy. In a pan-European series of 325 patients treated by this method, the mean age was 65 years (range 22–87). However, the administration of ^{90}Y microspheres and of ^{131}I -lipiodol is invasive as it involves

selective hepatic artery injection. Shunting to the lungs, normal liver and/or stomach may result in clinically significant short-term radiation burden (inducing pneumonitis, hepatitis or stomach ulceration). This may be particularly relevant in elderly patients with reduced pulmonary or liver function and potential additional gastric toxicity arising from concomitant medication.

An interesting application of radioembolisation is in the treatment of early-stage disease with a curative intent, given that 90% of yttrium-90 resin microspheres (^{90}Y)-treated tumours less than 3 cm and two-thirds of tumours of 3–5 cm show complete pathological necrosis (so-called radiation segmentectomy) [39]. Additionally, it has been observed that treatment of a lobe results in atrophy of that lobe and hypertrophy of the contralateral one, a characteristic that may aid in resection [40].

When considering a patient for radioembolisation, the tumour stage, liver function, renal function, performance status, α -fetoprotein level, coagulation parameters and goals of treatment must be taken into consideration. This is most reliably achieved through a multidisciplinary board.

Patients with poor hepatic reserve are less likely to tolerate a whole liver treatment. Other patients at high risk include those with disease affecting >50% of the liver, albumin less than 30 g/l (3 mg/dl), or bilirubin greater than 34.2 $\mu\text{mol/l}$ (2 mg/dl) [41]. Patients with impaired pulmonary status should also be examined carefully, because a significant lung shunt fraction is more likely to cause life-threatening radiation pneumonitis. Prior external beam radiation therapy is also considered a contraindication.

Radiopharmaceuticals are also being used with good palliative effect in metastatic or unresectable neuroendocrine tumours. These agents target either the noradrenaline transporter (in the case of ^{131}I -MIBG) or somatostatin receptor subtypes overexpressed on tumour cells using ^{90}Y linked to the somatostatin analogues octreotide or octreotate (^{90}Y -DOTATOC and -DOTATATE). With the latter agents, which accumulate in the renal cortex, renal toxicity is a concern, as is thrombocytopenia due to bone marrow toxicity. However, a study of more than 500 patients treated with DOTATATE found few adverse events (AEs) [42]. A recent review concluded that, while mild haematological toxicity with the two agents was common, renal toxicity was rare [43]. However, the mean age of the patients was 57 years (range not given), so the impact on elderly, frailer patients has not been established.

4.1. Bone-seeking agents

In relation to more prevalent cancers, the frequent occurrence of osseous metastases in advanced disease has focussed attention on the potential of bone metastasis-seeking radiopharmaceuticals. Of these, ^{89}Sr strontium, and ^{153}Sm samarium-ethylenediamine tetra

(methylene phosphonic acid) [EDTMP] emit β^- particles (electrons) with a few millimetre range and a relatively limited biological effect (Table 3.). The alpha emitter ^{223}Ra , on the other hand, has effects that are confined to a few cell diameters (<0.1 mm) but are more powerful. Whereas a β^- (electron) emitter may require more than a thousand DNA hits to achieve cell kill, this effect is achieved with only 1–4 hits from an alpha emitter. The fact that radiation damage is confined to the 40–100 μm area immediately surrounding ^{223}Ra molecules, rather than up to 12 mm with β^- emitters, suggests a reduced likelihood of adverse effects on nearby bone marrow.

While ^{89}Sr and ^{153}Sm -EDTMP have proven valuable in the relief of pain due to bone metastases in metastatic castration-resistant prostate cancer (mCRPC), ^{223}Ra has been shown in robust phase III studies to result in improved overall survival. Other radiopharmaceuticals have not been shown to have this effect [44]. Hence ^{223}Ra is a therapy to be considered alongside abiraterone or enzalutamide. In addition to its role in prolonging survival, the agent may provide effective pain relief.

Although important for all patients, patient preference is particularly relevant to the elderly in whom quality of life (QoL) is preeminent. In this context, it is worth noting that strontium-89 has been associated with well-maintained QoL in metastatic CRPC, and ^{223}Ra with improved QoL relative to placebo in the same setting [45,46]. There is a general reluctance to undergo chemotherapy if there are less toxic alternatives, and elderly patients may trade slightly reduced efficacy for higher quality of life or less risk of AEs. In metastatic CRPC, the almost simultaneous advent of life-prolonging androgen receptor targeting agents, immunotherapy, a novel taxane and a new radiopharmaceutical poses acute questions about the optimal sequencing and potential combination of treatments [31].

Use of therapeutic radiopharmaceuticals such as ^{223}Ra in the elderly, as in younger patients, is clearly

feasible. Given patients' more limited life expectancy, long-term toxicities, notably the risk of inducing a second cancer, are of less (if any) concern. This raises the question of whether their use in elderly patients should be governed by regulations less stringent than those applicable to the treatment of younger adults.

Risk of short term toxicities arising from damage to the kidneys and bone marrow may be exacerbated by reduced renal and marrow reserves. However, as treatment is fractionated over six cycles one month apart, radiation exposure on each occasion is one sixth or less of the maximum tolerated dose. Even so, there is the possibility that prior treatment with radiopharmaceuticals may mean that subsequent chemotherapy is less well tolerated, raising issues of optimal sequencing. Age, especially in combination with poor performance status (PS), is considered a risk factor for febrile neutropenia [47].

In the ALSYMPCA trial, 600 patients with CRPC were treated with ^{223}Ra and toxicities were generally mild [48]. The most frequently reported side-effects, occurring in more than 10% of patients, were anaemia, thrombocytopenia, constipation, nausea, diarrhoea, vomiting, fatigue, weight loss, anorexia, bone pain and peripheral oedema.

Grade 3–4 anaemia was reported in 13% of ^{223}Ra -treated patients, but this rate was not significantly different from that with placebo. anaemia seemed related to extensive disease rather than treatment-related; and patients experiencing anaemia did not suffer more than others from side-effects. Grade 3 or 4 thrombocytopenia occurred in 6% of ^{223}Ra -treated patients. One death from thrombocytopenia was reported. The fall in platelets seemed related to treatment, as it was less frequent with placebo, occurring in only 2% of patients. However, the 6% rate seen in patients receiving ^{223}Ra was still low. Grade 3–4 neutropenia occurred in 3% of treated patients.

It should be noted that certain toxicities associated with ^{223}Ra are of particular concern in the elderly. They

Table 3
Physical and clinical characteristics of therapeutic radiopharmaceuticals in current use for prostate cancer.

Agent	T $\frac{1}{2}$ d	Tissue penetration max (mean) mm	Standard dose	Efficacy	Toxicity
Strontium	50.5	5.5 (2.4)	148 MBq	Pain reduction: 33% CR; time to response 4–28 d; no OS benefit	Leucopenia in 20–80% and thrombocytopenia in 30–80% (both reversible); minimal anaemia
Samarium	1.9	2.5 (0.6)	37 MBq/kg	Pain relief in 83% of pts, complete in 31–38% no OS benefit	Reversible leucopenia in 40–50% of pts and thrombocytopenia in 20–42%
Radium	11.4	<0.1	50 kBq/kg	Significantly increased OS compared with control group (14.9 versus 11.3 months); significantly longer time to first skeletal event (15.6 versus 9.8 months)	Grade 3–4 anaemia in 13% of ^{223}Ra -treated patients was not significantly different from placebo. Gr 3–4 thrombocytopenia in 6% of treated patients versus 2% with placebo. Occasional cases of fatigue, nausea and loose stools; but toxicities in general are comparable with placebo.

are at greater risk in the case of diarrhoea, a known side-effect, leading to dehydration and possible kidney damage and other sequelae such as confusion and electrolyte disturbance; anaemia is less well-tolerated; and thrombocytopenia may be a particular problem in patients on anticoagulants.

The EMA-approved label for ^{223}Ra indicates that there are limited data on patients with moderate renal impairment, and no data on severe impairment or end-stage renal disease; and safety has not been studied in patients with hepatic impairment. However, as ^{223}Ra is not cleared through the kidneys, nor metabolised by the liver or eliminated via the bile, renal or hepatic impairment are not expected to affect its pharmacokinetics.

5. Radiopharmaceuticals in prostate cancer

Prospective phase III data in metastatic CRPC support the first-line use of docetaxel, enzalutamide and abiraterone (all of which significantly extend OS) and of sipuleucel-T and ^{223}Ra . These latter agents also extend OS but their pivotal trials also included patients who had had prior chemotherapy (though in the case of the sipuleucel-T trial, they amounted only to 15%) [49–53]. Second line, there are prospective data only for patients who had had prior docetaxel.

With regard to ^{223}Ra , the ALYSMPA trial included patients with CRPC metastatic to bone [48]. Fifty-seven percent had received prior docetaxel. The chemo-naïve

subgroup was not clearly defined and included patients unfit for chemotherapy, those unwilling to undergo it and those without access to it. Patients with visceral metastases and bulky lymph node disease were excluded.

Table 2 summarises current recommendations relevant to use of radiopharmaceuticals in mCRPC.

Of note, the 2016 European Association of Urology (EAU) guidelines on prostate cancer contain a section specific to management of the disease in elderly men, which should be undertaken by a multidisciplinary team [54]. In accord with the SIOG working group on prostate cancer [55], the EAU recommends use of the G8 screening tool for initial assessment of health status, followed when appropriate by full, specialist geriatric assessment to determine the reversibility of any impairments. Subsequent management should be based on an elderly patient's individual health status.

The role of newly developed agents for mCRPC has not been well defined in elderly men specifically. However, the relative ease of administering ^{223}Ra (i.v. every 4 weeks) and the fact that it seems generally well tolerated and does not interact with comedication may make it a good option in elderly patients, especially those with multiple comorbidities (Fig. 3). It would be of great help to randomise the new CRPC agents against each other in a trial specifically designed to include elderly patients and with a focus on quality of life and patient-reported outcomes.

When any of these recommendations go beyond existing data, they are phrased with caution, as is

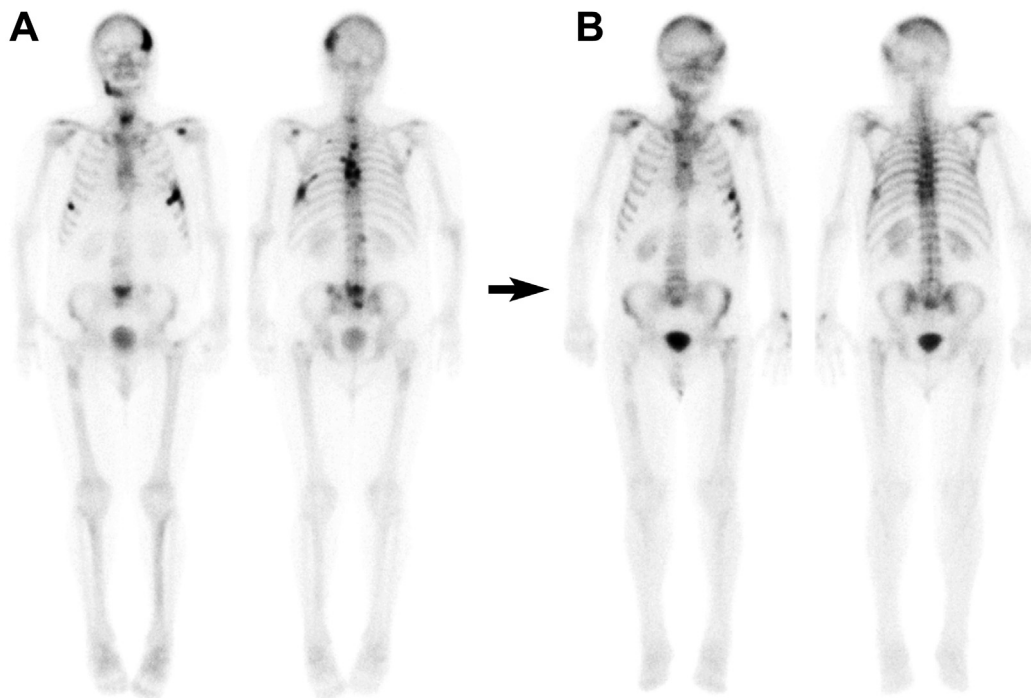


Fig. 3. Example of bone scintigraphic response in a 72-year old patient with metastatic castration-resistant prostate cancer and multiple bone metastases (A) in the skull, right hemi-jaw, left shoulder, ribs, thoracic and lumbar spine and (B) after six courses of ^{223}Ra over 6 months.

appropriate given the absence of comparative studies. Use of radiopharmaceuticals is cited as one of several options, but ^{223}Ra is linked to the presence of symptomatic bone metastases and the absence of visceral involvement—which implies that clinicians must look for such disease. Although PS is a factor in the AUA management plan, none of the recommendations is age-specific or accounts for age-associated factors such as comorbidities and frailty.

The NCCN suggests that estimation of remaining life expectancy is critical to informed decision making about disease management and recommends that clinicians consult the actuarial life tables. For patients judged to be in the best quartile of overall health, 50% should be added to the given life expectancy for age; and for patients in the poorest quartile, 50% should be deducted.

5.1. Guidance from trial data related to age

The pivotal trials mentioned above differ in their inclusion and exclusion criteria with respect to factors such as PS, the presence of visceral metastases and whether or not patients had received prior docetaxel. Within the recommendations, there is a certain amount of age-related evidence to guide choice of an agent for elderly patients. With docetaxel, the OS benefit in patients aged 75°years and in patients aged 65°years and above is similar to that in the wider population studied [49]. Forty percent of elderly patients had grade 3–4 AEs, and there was a greater need for dose reduction.

In the pivotal, placebo-controlled enzalutamide trial, 35% of enrolled patients were aged 75 or more [59]. The PFS and OS benefits of treatment were significant both in this age group and in younger patients. Similarly, in the pivotal trial versus mitoxantrone, the OS benefit of cabazitaxel was similar across prespecified subgroups, including patients aged 65 and above.

Table 3 shows the physical characteristics and clinical outcomes of currently available radiopharmaceuticals.

In the ALSYMPCA trial in men with CRPC and symptomatic bone metastases, the median age of patients enrolled was 71, and 28% were aged over 75°years [48]. The mean haemoglobin level of patients included was 12.2 g/dl, which seems higher than expected in routine practice for this patient population; and no data are given about comorbidities or geriatric functional assessment.

It is not clear how many of the patients who did not have prior docetaxel had refused chemotherapy, how many were judged unfit for chemotherapy, and how many had no access to it. It is therefore difficult to judge the efficacy and safety of this treatment in elderly patients. In the poorer PS group, the 0.73 HR for OS was in the same positive direction as for the population as a whole. However, the benefit of treatment did not achieve statistical significance; and, as with any subgroup

analysis, this finding can be considered only as hypothesis generating.

5.2. Protection and safety when using therapeutic radiopharmaceuticals

Protecting hospital staff, the general public and the environment from unnecessary exposure to radiation is a major concern in radiopharmaceutical diagnostics and therapy. Relevant regulations differ considerably from one country to another. For example, there have been concerns in Germany about the possibility of exhaled radon. Swiss patients given ^{223}Ra have to accept that cremation must be postponed (or burial used instead) if they die within seven days of its administration. Nuclear medicine physicians and technicians need to check which are applicable to the place they practice.

Elderly patients are more likely than their younger counterparts to require urgent surgery for conditions unrelated to cancer. In any patient with bone metastases, there is the possibility that fracture or spinal cord compression will necessitate surgical intervention. More generally, a patient's overall functional status — especially possible incontinence — is an age-related factor that is clearly relevant to radioprotection.

Appropriate radioprotection advice should be available to hospital staff when required in managing a patient recently treated with a radiopharmaceutical (protective eyewear for operating theatre staff and double pairs of gloves, for example, would be appropriate).

6. Discussion and conclusions

The use of radiopharmaceuticals to accurately image the spread of disease is of proven value. They are also likely to be useful in quantifying the burden of metabolically active tumour, which will further aid in personalising treatment. In relation to the elderly patient with significant comorbidities and limited life expectancy, the prognostic information such imaging could provide would be particularly valuable in enabling them to avoid unnecessary treatment and preserve quality of life.

When attempting to make recommendations for the elderly, it is striking to find that so few elderly patients have been entered into pivotal clinical trials, even of targeted anticancer agents [60]. In an ideal world, the proportion of elderly patients included in a trial would match the proportion of those with the disease. In the real world, there may be a case for providing companies with incentives to enrol such patients in key studies, or with requiring them to conduct trials specifically in the elderly, those who have comorbidities and those who are frailer [61].

The 50-year history of ^{131}I in thyroid tumours should give us confidence that radiopharmaceuticals can safely

Table 4

Take-home messages.

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- Include more elderly patients in pivotal clinical trials; this applies also to targeted anticancer agents
- The underrepresentation of elderly cancer patients in pivotal clinical trials restricts our ability to tailor management to their specific circumstances (comorbidities and frailty)
- Diagnostic radiopharmaceuticals are not an issue of particular concern in elderly patients, even in the presence of vulnerability
- Consider increasing isotope dose activity to decrease scan time and so minimise patient discomfort
- Therapeutic radiopharmaceuticals in elderly patients with hormone-resistant prostate cancer and symptomatic metastases are safe but require
 - assessment of short-term toxic effects on bone marrow and
 - adequate information to be given to patients, family members and care staff
 - More studies are needed on the combination of therapeutic radiopharmaceuticals with chemo- and/or other systemic therapies to determine if increased clinical benefit can be achieved with acceptable additional toxicity
-

be used in the treatment of cancer in a wide range of patients. However, with each new radioisotope and indication come unquantified risks. This applies both to the patients treated and to the staff treating them. In the elderly prostate cancer patient with symptomatic bone metastases and a life expectancy of less than 5° years, it is very unlikely that long-term effects of radiation exposure will become apparent. In a young woman with breast cancer, this is not necessarily the case. However, both kinds of patient must be assessed for the risk of short-term toxic effects, for example to bone marrow or the kidney. And staff administering radiopharmaceuticals are understandably concerned about the potential long-term impact of radiation on their general health and wellbeing, including fertility. Both patients and staff should be fully informed and given written information about risks.

Bone-seeking radiopharmaceuticals have no role in preventing the development of visceral metastases. While the risk of such involvement is initially low in prostate cancer, almost 50% of patients develop them at later stages of disease, and, with the prolongation of survival following the introduction of new drugs, this proportion is likely to increase [62]. Studies to assess whether the use of radiopharmaceuticals in combination with chemo- and other systemic therapies will increase clinical benefit with acceptable additional toxicity are now being conducted.

Since the relative costs of individual agents vary greatly from one health system and country to another, it is difficult to include such factors in clinical recommendations. However, the availability and cost of different agents are clearly relevant to the making of therapeutic decisions in the everyday management of the elderly, as with all cancer patients. [Table 4](#).

Conflict of interest statement

John Prior, William Dale and Manfred Wirth have nothing to disclose. Wim Oyen has served on advisory boards and the speakers' bureau for Bayer. Matti Aapro is or has been a consultant for Amgen, BMS, Celgene, Clinigen, Eisai, Genomic Health, GSK, Helsinn,

Hospira, JnJ, Novartis, Merck, Merck Serono, Mundipharma, Pfizer, Pierre Fabre, Roche, Sandoz, Tesaro, Teva, Vifor; he has received honoraria for lectures at symposia organised by Amgen, Bayer Schering, Cephalon, Chugai, Eisai, Genomic Health, GSK, Helsinn, Hospira, Ipsen, JnJ OrthoBiotech, Kyowa Hakko Kirin, Merck, Merck Serono, Mundipharma, Novartis, Pfizer, Pierre Fabre, Roche, Sandoz, Sanofi, Tesaro, Taiho, Teva, and Vifor. Silke Gillessen has served on advisory boards (compensated) for Astellas Pharma, Bayer, Curvac, Dendreon Corporation, Janssen, Millennium Pharmaceuticals, Novartis, Pfizer, Sanofi Aventis Group; and (uncompensated) on advisory boards for Astellas Pharma, ESSA Pharmaceuticals Corp, Nectar, Orion Corporation, ProteoMediX; on the speakers' bureau (compensated) for Astellas Pharma Europe, Bayer (Schweiz) AG; and on the speakers' bureau (uncompensated) for Amgen, Bayer, Janssen, Sanofi Aventis Group. She also declares a pending patent application for a method for biomarker WO 2009138392 A1.

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References

- [1] Pysz MA, Gambhir SS, Willmann JK. Molecular imaging: current status and emerging strategies. *Clin Radiol* 2010;65:500–16.
- [2] Wildiers H, Heeren P, Puts M, Topinkova E, Janssen-Heijnen ML, et al. International Society of Geriatric Oncology

- consensus on geriatric assessment in older patients with cancer. *J Clin Oncol* 2014;20:2595–603.
- [3] Droz J-P, Albrand G, Gillessen S, Hughes S, Mottet N, Oudard S, et al. Management of prostate cancer in elderly patients: recommendations of a Task Force of the International Society of Geriatric Oncology (SIOG). *Eur Urol* 2017 Jan 11. <http://dx.doi.org/10.1016/j.eururo.2016.12.025>.
 - [4] <http://seer.cancer.gov/statfacts/html/breast.html> [Accessed 19 January 2015].
 - [5] Rubini G, Nicoletti A, Rubini D, Asabella AN. Radiometabolic treatment of bone-metastasizing cancer: from 186rhenium to 223radium. *Cancer Biother Radiopharm* 2014;29:1–11.
 - [6] Frieling JS, Basanta D, Lynch CC. Current and emerging therapies for bone metastatic castrate-resistant prostate cancer. *Cancer Control* 2015;22:109–20.
 - [7] Bergman H, Ferrucci L, Guralnik J, Hogan DB, Hummel S, Karunanathan S, et al. Frailty: an emerging research and clinical paradigm - issues and controversies. *J Gerontol A Biol Sci Med Sci* 2007;62:731–7.
 - [8] Hurria A, Togawa K, Mohile SG, Owusu C, Klepin HD, Gross CP, et al. Predicting chemotherapy toxicity in older adults with cancer: a prospective multicenter study. *J Clin Oncol* 2011; 29:3457–65.
 - [9] Extermann M, Boler I, Reich RR, Lyman GH, Brown RH, DeFelice J, et al. Predicting the risk of chemotherapy toxicity in older patients: the Chemotherapy Risk Assessment Scale for High-Age Patients (CRASH) score. *Cancer* 2012;118:3377–86.
 - [10] D'Amico AV, Chen MH, Renshaw AA, Loffredo M, Kantoff PW. Androgen suppression and radiation vs radiation alone for prostate cancer: a randomized trial. *JAMA* 2008;299: 289–95.
 - [11] Hillner BE, Siegel BA, Liu D, Shields AF, Gareen IF, Hanna L, et al. Impact of positron emission tomography/computed tomography and positron emission tomography (PET) alone on expected management of patients with cancer: initial results from the National Oncologic PET Registry. *J Clin Oncol* 2008;26: 2155–61.
 - [12] Santos-Oliveira R. Undesirable events with radiopharmaceuticals. *Tohoku J Exp Med* 2009;217:251–7.
 - [13] Codreanu I, Dasanu CA, Weinstein GS, Divgi C. Fluorodeoxyglucose-induced allergic reaction: a case report. *J Oncol Pharm Pract* 2013;19:86–90.
 - [14] Lee DY, Lee JJ, Kwon HS, Moon WY, Jin SY, Lee S, et al. An unusual case of anaphylaxis after fluorine-18-labeled fluorodeoxyglucose injection. *Nucl Med Mol Imaging* 2013;47:201–4.
 - [15] Silberstein EB. Prevalence of adverse reactions to positron emitting radiopharmaceuticals in nuclear medicine. *Pharmacopeia Committee of the Society of Nuclear Medicine. J Nucl Med* 1998; 39:2190–2.
 - [16] Silberstein EB, Ryan J. Prevalence of adverse reactions in nuclear medicine. *Pharmacopeia Committee of the Society of Nuclear Medicine. J Nucl Med* 1996;37:185–92.
 - [17] Goyal J, Antonarakis ES. Bone targeting radiopharmaceuticals for the treatment of prostate cancer with bone metastases. *Cancer Lett* 2012;323:135–46.
 - [18] Scher HI, Morris MJ, Stadler NM, Higano C, Basch E, Fizazi K, et al. Trial design and objectives for castration-resistant prostate cancer: update recommendations from the prostate cancer clinical trials working group 3. *J Clin Oncol* 2016;34:1402–18.
 - [19] Hsu HH, Ko KH, Chou YC, Lin LF, Tsai WC, Lee SC, et al. SUVmax and tumor size predict surgical outcome of synchronous multiple primary lung cancers. *Medicine (Baltimore)* 2016 Feb;95: 2351. <http://dx.doi.org/10.1097/MD.0000000000002351> [2016 Epub].
 - [20] Machtay M, Duan F, Siegel BA, Snyder BS, Gorelick JJ, Reddin JS, et al. Prediction of survival by [18F]Fluorodeoxyglucose Positron Emission Tomography in patients with locally advanced non-small-cell lung cancer undergoing definitive chemoradiation therapy: results of the ACRIN 6668/RTOG 0235 trial. *J Clin Oncol* 2013;31:3823–30.
 - [21] Hasenclever D, Kurch L, Mauz-Körholz C, Elsner A, Georgi T, Wallace H, et al. qPET - a quantitative extension of the Deauville scale to assess response in interim FDG-PET scans in lymphoma. *Eur J Nucl Med Mol Imaging* 2014;41:1301–8.
 - [22] Senft A, de Bree R, Hoekstra OS, Kuik DJ, Golding RP, Oyen WJ, et al. Screening for distant metastases in head and neck cancer patients by chest CT or whole body FDG-PET: a prospective multicenter trial. *Radiother Oncol* 2008;87:221–9.
 - [23] Weber WA, Ott K, Becker K, Dittler HJ, Helmberger H, Avril NE, et al. Prediction of response to preoperative chemotherapy in adenocarcinomas of the oesophago-gastric junction by metabolic imaging. *J Clin Oncol* 2001;19:3058–65.
 - [24] Ott K, Fink U, Becker K, Stahl A, Dittler HJ, Busch R, et al. Prediction of response to preoperative chemotherapy in gastric carcinoma by metabolic imaging: results of a prospective trial. *J Clin Oncol* 2003;21:4604–10.
 - [25] Benz MR, Czernin J, Allen-Auerbach MS, Tap WD, Dry SM, Elashoff D, et al. FDG PET/CT imaging predicts histopathologic treatment responses after the initial cycle of neoadjuvant chemotherapy in high-grade soft-tissue sarcomas. *Clin Cancer Res* 2009;15:2856–63.
 - [26] Gavid M, Prevot-Bitot N, Timoschenko A, Gallet P, Martin C, Prades JM. [18F]-FDG PET-CT prediction of response to induction chemotherapy in head and neck squamous cell carcinoma: preliminary findings. *Eur Ann Otorhinolaryngol Head Neck Dis* 2014;132:3–7.
 - [27] Adkins D, Ley J, Dehdashti F, Siegel MJ, Wildes TM, Michel L, et al. A prospective trial comparing FDG-PET/CT and CT to assess tumor response to cetuximab in patients with incurable squamous cell carcinoma of the head and neck. *Cancer Med* 2014; 3:1493–501.
 - [28] Minamimoto R, Fayad L, Advani R, Vose J, Macapinlac H, Meza J, et al. Diffuse large B-cell lymphoma: prospective multicenter comparison of early interim FLT PET/CT versus FDG PET/CT with IHP, EORTC, Deauville, and PERCIST criteria for early therapeutic monitoring. *Radiology* 2016;280:220–9.
 - [29] Schöder H, Zelenetz AD, Hamlin P, Gavane S, Horwitz S, Matasar M, et al. Prospective study of 30-Deoxy-30-18F-Fluorothymidine PET for early interim response assessment in advanced-stage B-cell lymphoma. *J Nucl Med* 2016;57:728–34.
 - [30] MacManus MP, Hicks RJ. The role of positron emission tomography/computed tomography in radiation therapy planning. *Sem Nucl Med* 2012;42:308–19.
 - [31] Parker C, Gillessen S, Heidenreich A, Horwich A, on behalf of the ESMO Guidelines Committee. Cancer of the prostate: ESMO Clinical Practice Guidelines for diagnosis, treatment and follow up. *Ann Oncol* 2015;26(Suppl. 5):v69–77.
 - [32] Apolo AB, Lindenberg L, Shih JH, Mena E, Kim JW, Park JC, et al. Prospective study evaluating Na18F-Positron Emission Tomography-Computed Tomography (NAF-PET/CT) in predicting clinical outcomes and survival in advanced prostate cancer. *J Nucl Med* 2016;57:886–92.
 - [33] Evangelista L, Briganti A, Fanti S, Joniau S, Reske S, Schiavina R, et al. New clinical indications for 18F/11C choline, new tracers for positron emission tomography and a promising hybrid device for prostate cancer staging: a systematic review of the literature. *Eur Urol* 2016;70:161–75.
 - [34] Maurer T, Eiber M, Schwaiger M, Gschwend JE. Current use of PMSA-PET in prostate cancer management. *Nat Rev Urol* 2016; 13:226–35.
 - [35] Ahmadzadehfard H, Azgoni K, Hauser S, Wei X, Yordanova A, Gaertner FC, et al. 68Ga-PSMA-11 as a gatekeeper for the treatment of metastatic prostate cancer with radium-223: proof of concept. *J Nucl Med* 2017;58:438–44.
 - [36] Tenhunen M, Lehtonen S, Heikkonen J, Halonen P, Mäenpää H. First-day iodine kinetics is useful for individualizing radiation

- safety precautions for thyroid carcinoma patients. *Nucl Med Commun* 2013;34:1208–15.
- [37] Rao AV, Akabani G, Rizzieri DA. Radioimmunotherapy for Non-Hodgkin's lymphoma. *Clin Med Res* 2005;3:157–65.
- [38] Sangro B, Carpanese L, Cianni R, Golfieri R, Gasparini D, Ezziddin S, et al. Survival after yttrium-90 resin microsphere radioembolization of hepatocellular carcinoma across Barcelona clinic liver cancer stages: a European evaluation. *Hepatology* 2011;54:868–78.
- [39] Orlando A, Leandro G, Olivo M, Andriulli A, Cottone M. Radiofrequency thermal ablation vs percutaneous ethanol injection for small hepatocellular carcinoma in cirrhosis. Meta-analysis of randomized controlled trials. *Am J Gastroenterol* 2009;104:514–24.
- [40] Gaba RC, Lewandowski RJ, Kulik LM, Riaz A, Ibrahim SM, Mulcahy MF, et al. Radiation lobectomy. Preliminary findings of hepatic volumetric response to lobar yttrium-90 radioembolization. *Ann Surg Oncol* 2009;16:1587–96.
- [41] Salem R, Thurston KG. Radioembolization with (90)yttrium microspheres. A state-of-the-art brachytherapy treatment for primary and secondary liver malignancies, Part 1 technical and methodologic considerations. *J Vasc Interv Radiol* 2006;17:1251–78.
- [42] Kwekkeboom DJ, de Herder WW, Kam BL, van Eijck CH, van Essen M, Kooij PP, et al. Treatment with the radiolabeled somatostatin analog [177 Lu-DOTA 0, Tyr3] octreotate: toxicity, efficacy, and survival. *J Clin Oncol* 2008;26:2124–30.
- [43] Vinjamuri S, Gilbert TM, Banks M, McKane G, Maltby P, Poston G, et al. Peptide radionuclide therapy with (90)Y-DOTATATE/(90)Y-DOTATOC in patients with progressive metastatic neuroendocrine tumours: assessment of response, survival and toxicity. *Br J Cancer* 2013;108:1440–8.
- [44] Florimonte L, Dallavedova L, Maffioli LS. Radium-223 dichloride in clinical practice: a review. *Eur J Nucl Med Mol Imaging* 2016;43:1896–909.
- [45] Nilsson S, Cislo P, Sartor O, Vogelzang NJ, Coleman RE, O'Sullivan JM, et al. Patient-reported quality of life analysis of radium-223 dichloride from the phase III ALSYMPCA study. *Ann Oncol* 2016;27:868–74.
- [46] James N, Pirrie S, Pope A, Barton D, Andronis L, Goranitis I, et al. TRAPEZE: a randomized controlled trial of the clinical effectiveness and cost-effectiveness of chemotherapy with zoledronic acid, strontium-89, or both, in men with bony metastatic castration refractory prostate cancer. *Health Technol Assess* 2016;20:1–288.
- [47] v2 NCCN clinical practice guidelines in oncology: myeloid growth factors. 2014.
- [48] Parker C, Nilsson S, Heinrich D, Helle SI, O'Sullivan JM, Fossà SD, et al. Alpha emitter radium-223 and survival in metastatic prostate cancer. *N Engl J Med* 2013;369:213–23.
- [49] Berthold DR, Pond GR, Soban F, de Wit R, Eisenberger M, Tannock IF. Docetaxel plus prednisone or mitoxantrone plus prednisone for advanced prostate cancer: updated survival in the TAX 327 study. *J Clin Oncol* 2008;26:242–5.
- [50] Beer TM, Armstrong AJ, Rathkopf DE, Loriot Y, Sternberg CN, Higano CS, et al. Enzalutamide in metastatic prostate cancer before chemotherapy. *N Engl J Med* 2014;371:424–33.
- [51] Kantoff PW, Higano CS, Shore ND, Berger ER, Small EJ, Penson DF, et al. Sipuleucel-T immunotherapy for castration-resistant prostate cancer. *N Engl J Med* 2010;363:411–22.
- [52] Ryan CJ, Smith MR, de Bono JS, Molina A, Logothetis CJ, de Souza P, et al. Abiraterone in metastatic prostate cancer without previous chemotherapy. *N Engl J Med* 2013;368:138–48.
- [53] Ryan C, Smith MR, Fizazi K, Fizazi K, Saad F, Mulders PF, et al. Abiraterone acetate plus prednisone versus placebo plus prednisone in chemotherapy-naïve men with metastatic castration-resistant prostate cancer(COU-AA-302): final overall survival analysis of a randomised, double-blind, placebo-controlled phase 3 study. *Lancet Oncol* 2015;16:152–60.
- [54] Mottet N, Bellmunt J, Bolla M, Briers E, Cumberbatch MG, De Santis M, et al. EAU-ESTRO-SIOG guidelines on prostate cancer. *Eur Urol* 2017;71:618–29.
- [55] Droz JP, Aapro M, Balducci L, Boyle H, Van den Broeck T, Cathcart P, et al. Management of prostate cancer in senior adults: updated recommendations of a working group of the International Society of Geriatric Oncology (SIOG). *Lancet Oncol* 2014;15:404–14.
- [56] v2 NCCN clinical practice guidelines in oncology: prostate cancer. 2016.
- [57] Lowrance WT, Roth BJ, Kirkby E, Murad MH, Cookson MS, American Urological Association. Castration-resistant prostate cancer: AUA guideline. *J Urol* 2016;195:1444–52.
- [58] Basch E, Loblaw A, Oliver TK, Carducci M, Chen RC, Frame JN, et al. Systemic therapy in men with metastatic castrate-resistant prostate cancer: American Society of Clinical Oncology and Cancer Care Ontario Clinical Practice Guidelines. *J Clin Oncol* 2014;32:3436–48.
- [59] Beer TM, Armstrong AJ, Rathkopf DE, Loriot Y, Sternberg CN, Higano CS, et al. Enzalutamide in metastatic prostate cancer patients before chemotherapy. *New Engl J Med* 2014;371:424–33.
- [60] Kelly CM, Power DG, Lichtman SM. Targeted therapy in older patients with solid tumors. *J Clin Oncol* 2014;32:2635–46.
- [61] Hurria A, Dale W, Mooney M, Rowland JH, Ballman KV, Cohen HJ, et al. Designing therapeutic clinical trials for older and frail adults with cancer: U13 conference recommendations. *J Clin Oncol* 2014;32:2587–94.
- [62] Pezaro CJ, Omlin A, Lorente D, Nava Rodrigues D, Ferraldeschi R, Bianchini D, et al. Visceral disease in castration-resistant prostate cancer. *Eur Urol* 2014;65:270–3.