Purpose of review
Primary aldosteronism is increasingly recognized as a common secondary cause of hypertension. Successful demonstration of a unilateral cause (e.g. a classical ‘Conn’s adenoma’) offers the potential for curative adrenalectomy. Adrenal vein sampling (AVS), in conjunction with cross-sectional imaging, remains the ‘gold standard’ for distinguishing unilateral and bilateral disease, but is technically demanding and frequently unsuccessful or inconclusive. As such, alternative strategies for lateralization, including nuclear medicine techniques, are being developed and brought into clinical practice.

Recent findings
Metomidate, a potent ligand of CYP11B1 and CYP11B2, can be $^{11}$H$_3$-labelled as a PET tracer and has been shown to offer a rapid noninvasive alternative to AVS for localizing unilateral aldosterone-producing adenomas.

Summary
Increasing experience with $^{11}$C-metomidate PET-CT supports its use as an adjunct to AVS when this has failed, is ambiguous, or cannot be undertaken.

Keywords
metomidate, PET-CT, primary aldosteronism/hyperaldosteronism

INTRODUCTION
Hypertension is a major determinant of excess cardiovascular morbidity and mortality, especially myocardial infarction, and stroke. Well established algorithms for stepwise pharmacological management of ‘essential’ hypertension exist, alongside lifestyle interventions [1*]. However, identifying a specific cause for hypertension, such as primary (hyper)aldosteronism, yields the possibility of targeted drug therapy or, more enticingly, the potential for surgical cure. Indeed, the impetus to diagnose and manage primary aldosteronism is further strengthened by the recognition that aldosterone excess is associated with morbidity over and above that in a matched population with primary hypertension [2]. Primary aldosteronism is increasingly recognized as a common secondary cause of hypertension and is reported in approximately 5–10% of all hypertensive patients and in 20–25% of those with documented treatment-resistant hypertension [3,4]. In around half of all cases of primary aldosteronism, the hypersecretion is attributable to a single aldosterone-producing adenoma (APA) in one adrenal gland, and when this is the case adrenalectomy offers the possibility of a cure of hypertension in a significant proportion of patients. However, currently only one in 10 eligible patients proceed to surgery [3]. Perhaps the most significant hurdle is the need to confirm that primary aldosteronism is indeed the result of unilateral disease, thus distinguishing an isolated APA from other causes of primary aldosteronism, including bilateral idiopathic hyperaldosteronism.
and familial syndromes, which may coexist with a nonfunctioning adrenal adenoma (incidentaloma) [5]. Currently, nonlateralizing primary aldosteronism is treated medically, but this has been shown to have poorer cardiovascular outcomes than surgery for unilateral disease [6,7].

ADRENAL VEIN SAMPLING IN THE DIAGNOSIS OF PRIMARY ALDOSTERONISM

The first step in establishing lateralization typically involves cross-sectional imaging [thin-slice computed tomography (CT) or MRI]. In patients under 35 years of age, the finding of a classical solitary Conn’s adenoma (1–2 cm diameter), with an entirely normal contralateral gland may be sufficient to proceed direct to surgery [8]. In the majority of cases however, further proof of unilateral hyperplasia is required, as several studies have shown that reliance on cross-sectional imaging alone is fraught with risk. This is nonspecific, as nonfunctioning adrenal incidentalomas are common in patients more than 40 years of age (4–7% of the population) [5]. It is also insensitive as small nodules (<1 cm in diameter) may be missed, especially if located within the body of the adrenal, and a common sub-tier of small APAs was recently identified through finding hallmark somatic mutations, distinct from those in classical Conn’s adenomas [9*]. The gold-standard lateralization procedure remains bilateral adrenal vein sampling (AVS) [10]. However, this is technically challenging and in many centres the right adrenal vein is successfully cannulated in only 50–80% of cases [11,12]. In addition, several different sets of criteria exist for defining both successful adrenal vein cannulation and subsequently lateralization, based on the measurement of plasma cortisol and aldosterone levels in both adrenal veins and in the inferior vena cava [13]. In recognition, that both cortisol and aldosterone secretion can be pulsatile, some centres perform AVS with cosyn- tropin stimulation and/or sampling of the adrenal veins simultaneously, rather than sequentially. Both measures aim to reduce the risk of false lateralization [14,15*].

The difficulties inherent in achieving successful AVS, coupled with the potential need for many more patients to be referred for lateralizing studies as primary aldosteronism is increasingly recognized, has led to a search for alternative strategies to circumvent the ‘hurdle’ of AVS in progressing patients to surgery. Küpers et al. [16] assessed the potential utility of a clinical scoring system in predicting unilateral disease. In 87 patients with primary aldosteronism and successful AVS, lateralization was demonstrated in 49 patients. All 26 patients with a typical Conn’s adenoma and serum potassium level less than 3.5 mmol/l or estimated glomerular filtration rate at least 100 ml/min/1.73 m² (or both) had unilateral primary aldosteronism; this rule had 100% specificity and 53% sensitivity. However, subsequent studies from both the UK [17*] and Germany (German Conn’s Registry) [18*] were unable to reproduce the 100% specificity (88.5 and 80%, respectively). Accordingly, interest has been rekindled in functional imaging techniques to complement cross-section imaging and AVS and which would allow a more definitive assessment of lateralization to be delivered to many more patients than is currently achievable in the majority of centres.

NUCLEAR MEDICINE IMAGING IN THE DIAGNOSIS OF PRIMARY ALDOSTERONISM

Norcholesterol scintigraphy

Historically, 131I-iodomethyl-norcholesterol (NP-59) and 75Se-selenomethyl-19-norcholesterol have been used as scintigraphic tracers for the detection of APAs [19,20]. In both cases, high dose dexamethasone treatment (e.g. 8 mg per day for >1 week) to suppress tracer uptake by nonautonomous adrenal cortex is given, and patients are required to attend for image capture on several occasions. In addition, the accuracy of distinguishing an APA from bilateral hyperplasia is as low as 47% in studies using planar imaging, which in particular lacks the resolution to reliably detect lesions less than 1.5–2 cm in diameter. It may also erroneously identify gastrointestinal activity as adrenal uptake. Single photon emission computed tomography/CT has been proposed as a means of addressing these concerns, although significant numbers of false-positive and false-negative categorizations have been observed even in modern case series [21].
Although attempts have been made to improve sensitivity and specificity with semiquantitative approaches to this technique [22**, the requirement for prolonged dexamethasone suppression, sequential imaging, and limited tracer availability mean that it is unlikely to be considered a viable alternative to AVS in most centres.

**11C-metomidate PET-CT**

Recent interest has focussed on the potential utility of PET-CT, with its increased spatial resolution, as an alternative imaging modality for the detection of functional autonomy in primary aldosteronism. Metomidate is a potent inhibitor of CYP11B1 (11B-hydroxylase) and CYP11B2 (aldosterone synthase). It is the methyl analogue of etomidate, an ethyl-imidazole anaesthetic agent which is used clinically in subhypnotic doses as an inhibitor of adrenal steroidogenesis in the management of refractory Cushing’s syndrome [23]. Metomidate (itself used as a veterinary anaesthetic until the 1970s) can be C\(^{11}\)H\(_3\)-labelled as a PET radiotracer (\(^{11}\)C-metomidate), and proof of concept of its high affinity binding to adrenal cortex was established *in vitro* and in primate studies as far back as 1998 [24]. In the first human application [25], 15 patients underwent \(^{11}\)C-methionine PET-CT prior to surgery for a unilateral adrenal mass. The nine histologically diagnosed adrenocortical tumours each demonstrated high uptake and could be reliably discriminated from the six lesions that were not of cortical origin. In a larger follow-up series, comprising 73 patients who underwent surgery for suspected adrenal lesions, the six histologically confirmed APAs demonstrated the highest \(^{11}\)C-metomidate uptake, with a standardized uptake value (SUV) of 30.7 compared with 18.4 in nonfunctional adenomas [26]. These findings suggested that \(^{11}\)C-metomidate PET-CT might offer an alternative technique for the localization of Conn’s adenomas and provided preliminary evidence to support a formal study of sensitivity and specificity in an unselected cohort of patients with unilateral and bilateral primary aldosteronism.

We recently reported the findings of such a study in which the potential utility of \(^{11}\)C-metomidate PET-CT for establishing lateralization in primary aldosteronism was assessed through direct comparison with the current ‘gold standard’ of AVS in a prospective noninferiority trial [27**]. Based on the findings of a small pilot study, all patients received a short course of low-dose dexamethasone (0.5 mg 6-hourly for 72 h) immediately prior to undergoing a single PET-CT scan. This well tolerated pretreatment regimen improved the signal to background ratio through suppression of \(^{11}\)C-metomidate uptake by nonadenomatous adrenal cortex. Interestingly, pretreatment with fludrocortisone (400 µg daily), either alone or in combination with the dexamethasone, showed no additional benefit. Of 44 recruited individuals, 39 had primary aldosteronism and five a nonfunctioning adrenal incidentaloma (these individuals were normotensive and had no clinical or biochemical evidence of adrenal hyperfunction). In the group with primary aldosteronism, 19 had a unilateral cause identified at AVS, and a further six were confirmed to have unilateral disease on the basis that subsequent unilateral adrenalectomy reversed their biochemical primary aldosteronism and cured their hypertension, despite a failure to conclusively lateralize on AVS (the decision to recommend surgery in these cases was taken independently by the referring physician with primary responsibility for the patient’s care). Of those deemed to have unilateral primary aldosteronism on AVS, all but three proceeded to surgery. All operated cases demonstrated a histological adenoma with dominant CYP11B2 expression, and aldosterone production in primary culture of cells from the resected nodule, which exceeded that of adjacent normal tissue. Ten patients met the criteria for a diagnosis of bilateral primary aldosteronism. Four patients were excluded from the final analysis as they did not proceed to surgery, in the absence of a clear-cut AVS result and indication for surgery.

\(^{11}\)C-metomidate uptake was calculated as the SUV\(_{\text{max}}\) during the final 10 min of data acquisition. In patients with primary aldosteronism and a unilateral APA, the mean SUV\(_{\text{max}}\) over the adenoma [21.7 ± 1.6 (range 10.3–38.9)] was significantly greater than in the surrounding normal adrenal tissue SUV\(_{\text{max}}\) [13.8 ± 0.6 (P < 0.00003)] [27**]. Patients with an adrenal incidentaloma (and no clinical or biochemical evidence of primary aldosteronism) demonstrated a lower mean tumour SUV\(_{\text{max}}\) of 11.5 ± 3.3 (range 0–16.6). Patients with primary aldosteronism and bilateral adrenal hyperplasia or bilateral adenomas had a mean SUV\(_{\text{max}}\) of 17.3 ± 1.2 [27**]. Calculation of the ratio of tumour SUV\(_{\text{max}}\) to normal background adrenal SUV\(_{\text{max}}\) revealed that an SUV ratio greater than 1.25 afforded optimal sensitivity (76%) and specificity (87%). Importantly, specificity increased to 100% in patients with an SUV\(_{\text{max}}\) ratio greater than 1.25 and absolute tumour SUV\(_{\text{max}}\) of greater than 17 [27**].

Taken together, these findings provide confirmatory evidence that \(^{11}\)C-metomidate PET-CT offers a noninferior alternative to AVS in the diagnosis of unilateral primary aldosteronism. Since our original
FIGURE 1. Case 1 – $^{11}$C-metomidate PET-CT identifies unilateral primary aldosteronism in a patient with equivocal cross-sectional imaging. A 56-year-old man with significant ischaemic coronary disease had poorly controlled hypertension despite treatment with multiple agents. Further investigation confirmed a diagnosis of primary aldosteronism. CT revealed an 8 mm lipid poor right adrenal nodule, which could not be fully characterized because of its small size (a). In addition, the body of the left adrenal gland was noted to be bulky, but without a discrete lesion. Adrenal vein sampling (AVS) demonstrated a right-sided gradient (>4:1), but in light of the equivocal cross-sectional imaging findings the patient proceeded to $^{11}$C-metomidate PET-CT. This confirmed increased tracer uptake [target:background standardized uptake value (SUV)$_{\text{max}}$ ratio 1.44] in the right adrenal nodule only (b). The patient underwent laparoscopic right adrenalectomy, which confirmed a classical small Conn’s adenoma. Postoperatively, he had complete resolution of his hyperaldosteronism and required just single agent therapy (amlodipine) to achieve satisfactory blood pressure control. This case illustrates how the increased spatial resolution of $^{11}$C-metomidate PET-CT facilitates the reliable identification of subcentimetre Conn’s adenomas.

FIGURE 2. Case 2 – $^{11}$C-metomidate PET-CT identifies unilateral primary aldosteronism despite mineralocorticoid receptor antagonist therapy. A 63-year-old man with a 10-year history of primary aldosteronism treated medically with mineralocorticoid receptor antagonist therapy was referred for reassessment and consideration of possible adrenalectomy. His blood pressure had previously proved difficult to control until the introduction of spironolactone, and the patient was reluctant to discontinue this to permit adrenal vein sampling (AVS). MRI demonstrated an 11 mm right adrenal nodule (a). $^{11}$C-metomidate PET-CT confirmed avid tracer uptake within this lesion [target:background standardized uptake value (SUV)$_{\text{max}}$ ratio 2.45] (b). He underwent laparoscopic right adrenalectomy, with histology confirming an adrenal cortical adenoma. Postoperatively, he had complete resolution of his biochemical hyperaldosteronism and hypertension with no requirement for antihypertensive therapy. This case illustrates the utility of $^{11}$C-metomidate PET-CT in establishing unilateral primary aldosteronism even in patients who are unable or unwilling to discontinue mineralocorticoid receptor antagonist therapy.
study, we have confirmed and extended our findings in a much larger cohort of patients (illustrative cases, Figs. 1–4), with confirmation that PET-CT confers significant benefits particularly with respect to the identification of small APAs (where the enhanced spatial resolution compared with conventional scintigraphy is required), and in patients in whom AVS is technically challenging, inconclusive or not feasible.

The downside of $^{11}$C-metomidate PET-CT is the 20-min half-life of $^{11}$C-isotopes, mandating an on-site cyclotron. Two patients can be studied for each synthesis, making the costs comparable to, or lower than, those for AVS, and a number of centres in the UK and Scandinavia are now establishing and evaluating $^{11}$C-metomidate PET-CT. Elsewhere, there is interest in radiolabels with longer half-lives, with $^{123}$I-metomidate or $^{131}$I-metomidate being used in the diagnosis and therapy of malignant adrenocortical carcinomas [28**]. However, the different analogues may vary in relative affinity for the aldosterone-producing and cortisol-producing enzymes (CYP11B2 and CYP11B1), with critical difference therefore in their ability to distinguish APAs from adjacent adrenal tissue [29]. They may also lack the spatial resolution afforded by PET-CT.

CONCLUSION

Primary aldosteronism is a common cause of hypertension and in unilateral disease, which accounts for approximately 50% of cases, is potentially curable surgically. Lateralization with AVS is technically demanding and invasive and in many centres is frequently unsuccessful. $^{11}$C-metomidate PET-CT offers a rapid noninvasive alternative to AVS for
localizing unilateral APAs. Our increasing experience suggests it may have particular utility in certain settings, such as when mineralocorticoid receptor antagonists cannot be easily or safely withdrawn, or with subcentimetre lesions and equivocal cross-sectional imaging. Furthermore, in our experience patients universally prefer this noninvasive option.

Acknowledgements
The authors acknowledge the contribution of Dr H.K. Cheow and Dr J. Buscombe of the Departments of Nuclear Medicine and Radiology, Addenbrooke’s Hospital, Cambridge, UK.

Financial support and sponsorship
A.S.P. and M.G. are supported by the National Institute for Health Research Cambridge Biomedical Research Centre. M.J.B. is a National Institute of Health Research Senior Investigator.

Conflicts of interest
There are no conflicts of interest.

REFERENCES AND RECOMMENDED READING
Papers of particular interest, published within the annual period of review, have been highlighted as:

■ of special interest
■■ of outstanding interest

1. Go AS, Bauman MA, Coleman King SM, et al. An effective approach to high blood pressure control: a science advisory from the American Heart Association, the American College of Cardiology, and the Centers for Disease Control and Prevention. J Am Coll Cardiol 2014; 63:1290–1238.

2. Milliez P, Girerd X, Ploun PF, et al. Evidence for an increased rate of cardiovascular events in patients with primary aldosteronism. J Am Coll Cardiol 2005; 45:1243–1248.

3. Rossi GP. A comprehensive review of the clinical aspects of primary aldosteronism. Nat Rev Endocrinol 2011; 7:485–495.

4. Calhoun DA, Nishizaka MK, Zaman MA, et al. Hyperaldosteronism among black and white subjects with resistant hypertension. Hypertension 2002; 40:892–896.

5. Young WF Jr. Clinical practice. The incidentally discovered adrenal mass. N Engl J Med 2007; 356:601–610.

6. Catena C, Colussi G, Lapenna R, et al. Long-term cardiac effects of adrenalectomy or mineralocorticoid antagonists in patients with primary aldosteronism. Hypertension 2007; 50:911–918.

7. Bernini G, Bacca A, Cari V, et al. Cardiovascular changes in patients with primary aldosteronism after surgical or medical treatment. J Endocrinol Invest 2012; 35:274–280.

8. Young WF. Primary aldosteronism: renaissance of a syndrome. Clin Endocrinol (Oxf) 2007; 66:607–618.

9. Azizan EA, Poulsen H, Tuluc P, et al. Somatic mutations in ATP1A1 and CACNA1D underlie a common subtype of adrenal hypertension. Nat Genet 2013; 45:1055–1060.

10. Establishes both a novel genetic mechanism for sporadic APAs and the concept of the ‘small’ Conn’s adenoma as a pathogenetically distinct subtype.

11. Funder JW, Carey RM, Fardella C, et al. Case detection, diagnosis, and treatment of patients with primary aldosteronism: an Endocrine Society clinical practice guideline. J Clin Endocrinol Metab 2008; 93:3266–3281.

12. Harvey A, Kline G, Pasieka JL. Adrenal venous sampling in primary hyperaldosteronism. Hypertension 2007; 50:911–918.

13. Milliez P, Girerd X, Ploun PF, et al. Evidence for an increased rate of cardiovascular events in patients with primary aldosteronism. J Am Coll Cardiol 2005; 45:1243–1248.

14. Rossi GP, Barisa M, Allolio B, et al. The Adrenal Vein Sampling International Study (AVIS) for identifying the major subtypes of primary aldosteronism. J Clin Endocrinol Metab 2012; 97:1606–1614.

15. Rossi GP, Auchus RJ, Brown M, et al. An expert consensus statement on the OECD consensus on the management of hypertension.

16. Küppers EM, Amar L, Raynaud A, et al. A clinical prediction score to diagnose unilateral primary aldosteronism. J Clin Endocrinol Metab 2012; 97:3530–3537.

17. Sze WC, Soh LM, Lau JH, Reznik R, et al. Diagnosing unilateral primary aldosteronism – comparison of a clinical prediction score, computed tomography and adrenal venous sampling. Clin Endocrinol (Oxf) 2014; 81:25–30.

An evaluation of the clinical prediction score of Küppers et al. [16], failing to reproduce the specificity of the original study.

18. Riester A, Fischer E, Degenhart C, et al. Age below 40 or a recently proposed clinical prediction score cannot bypass adrenal venous sampling in primary aldosteronism. J Clin Endocrinol Metab 2014; 99:E1035–E1039.

An evaluation of the clinical prediction score of Küppers et al. [16], failing to reproduce the specificity of the original study.
19. Rubello D, Bui C, Casara D, Gross MD, et al. Functional scintigraphy of the adrenal gland. Eur J Endocrinol 2002; 147:13–28.
20. Volpe C, Enberg U, Sjögren A, et al. The role of adrenal scintigraphy in the preoperative management of primary aldosteronism. Scand J Surg 2008; 97:248–253.
21. Yen RF, Wu VC, Liu K, et al. 131I-8beta-iodomethyl-19-norcholesterol SPECT/CT for primary aldosteronism patients with inconclusive adrenal venous sampling and CT results. J Nucl Med 2009; 50:1631–1637.
22. Lo CC, Wu VC, Wu KD, et al. Prognostic value of semiquantification NP-59 SPECT/CT in primary aldosteronism patients after adrenalectomy. Eur J Nucl Med Mol Imaging 2014; 41:1375–1384.
23. Preda VA, Sen J, Karavitaki N, Grossman AB. Etomidate in the management of hypercortisolaemia in Cushing’s syndrome: a review. Eur J Endocrinol 2012; 167:137–143.
24. Bergström M, Bonasera TA, Lu L, et al. In vitro and in vivo primate evaluation of carbon-11-etomidate and carbon-11-metomidate as potential tracers for PET imaging of the adrenal cortex and its tumors. J Nucl Med 1998; 39:982–989.
25. Bergström M, Juhlin C, Bonasera TA, et al. PET imaging of adrenal cortical tumors with the 11-beta-hydroxylase tracer 11C-metomidate. J Nucl Med 2000; 41:275–282.
26. Hennings J, Lindhe O, Bergström M, et al. 11C-metomidate positron emission tomography of adrenocortical tumors in correlation with histopathological findings. J Clin Endocrinol Metab 2006; 91:1410–1414.
27. Burton TJ, Mackenzie IS, Balan K, et al. Evaluation of the sensitivity and specificity of 11C-metomidate positron emission tomography PET-CT for lateralizing aldosterone secretion by Conn’s adenomas. J Clin Endocrinol Metab 2012; 97:100–109.
28. Kreissl MC, Schirbel A, Fassnacht M, et al. 123I-Iodometomidate imaging in adrenocortical carcinoma. J Clin Endocrinol Metab 2013; 98:2755–2764.
29. Hahner S, Stuermer A, Kreissl M, et al. 123I-Iodometomidate for molecular imaging of adrenocortical cytochrome P450 family 11B enzymes. J Clin Endocrinol Metab 2008; 93:2358–2365.